Spaceguard Survey

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The Spaceguard Survey

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The Spaceguard Survey

Executive Summary

Background. *Impacts by Earth-approaching asteroids and comets pose a significant hazard to life and property. Although the annual probability of the Earth being struck by a large asteroid or comet is extremely small, the consequences of such a collision are so catastrophic that it is prudent to assess the nature of the threat and prepare to deal with it. The first step in any program for the prevention or mitigation of impact catastrophes must involve a comprehensive search for Earth-crossing asteroids and comets and a detailed analysis of their orbits. At the request of the U.S. Congress, NASA has carried out a preliminary study to define a program for dramatically increasing the detection rate of Earth-crossing objects, as documented in this Workshop Report.*

Impact Hazard. *The greatest risk from cosmic impacts is associated with objects large enough to perturb the Earth's climate on a global scale by injecting large quantities of dust into the stratosphere. Such an event could depress temperatures around the globe, leading to massive loss of food crops and possible breakdown of society. Such global catastrophes are qualitatively different from other more common hazards that we face (excepting nuclear war), because of their potential effect on the entire planet and its population. Various studies have suggested that the minimum mass impacting body to produce such global consequences is several tens of billions of tons, resulting in a groundburst explosion with energy in the vicinity of a million megatons of TNT. The corresponding threshold diameter for Earth-crossing asteroids or comets is between 1 and 2 km . Smaller objects (down to tens of meters diameter) can cause severe local damage but pose no global threat.*

Search Strategy *Current technology permits us to discover and track nearly all asteroids or short-period comets larger than 1 km diameter that are potential Earth-impactors. These objects are readily detected with moderate-size ground-based telescopes. Most of what we now know about the population of Earth-crossing asteroids (ECAs) has been derived over the past two decades from studies carried out by a few dedicated observing teams using small ground-based telescopes. Currently several new ECAs are discovered each month. At this rate, however, it will require more than a century to approach a complete* *survey, even for the larger objects. What is required to assess the population of ECAs and identify any large objects that could impact the Earth is a systematic survey that effectively monitors a large volume of space around our planet and detects these objects as their orbits repeatedly carry them through this volume of space. In addition, the survey should deal with the long-period comets, which are thought to constitute about 10 percent of the flux of Earth impacts. Long-period comets do not regularly enter near-Earth space; however, nearly all Earth-impacting long-period comets could be detected with advance warning on the order of a year before impact with the same telescopes used for the ECA survey. Finally, it is desirable to discover as many of the smaller potential impactors as possible.*

Lead Time. *No object now known has an orbit that will lead to a collision with our planet during the next century, and the vast majority of the newly discovered asteroids and comets will also be found to pose no near-term danger. Even if an ECA has an orbit that might lead to an impact, it will typically make hundreds of moderately near passes before there is any danger, providing ample time for response. However, the lead time will be much less for a new comet approaching the Earth on a long-period orbit, as noted above.*

Spaceguard Survey Network. *The survey outlined in this report involves a coordinated international network of specialized ground-based telescopes for discovery, confirmation, and follow-up observations. Observations are required from both the northern and southern hemispheres, monitoring about 6000 square degrees of sky per month. In order to provide reliable detection of objects as small as 1 km diameter over a suitably large volume of space, the telescopes should reach astronomical magnitude 22. The telescopes that are suitable to this survey have apertures of 2-3 meters, moderately wide fields of view (2-3 degrees), focal-plane arrays of large-format CCD detectors, and automated signal processing and detection systems that recognize the asteroids and comets from their motion against the background of stars. The technology for such automated survey telescopes has been demonstrated by the 0.9-m Spacewatch telescope of the University of Arizona. For purposes of this study, we focus on a Spaceguard Survey network of six 2.5-m aperture, f/2 prime focus reflecting telescopes each with four 2048x2048 CCD chips in the focal plane.*

Follow-up and Coordination. *In addition to the discovery and verification of new Earth-approaching asteroids and comets, the Spaceguard Survey program will require follow-up observations to refine orbits, determine the sizes of newly-discovered objects, and establish the physical properties of the asteroid and comet population.*

Observations with large planetary radars are an especially effective tool for the rapid determination of accurate orbits, but are not useful as a primary search method because of their limited range. Potentially hazardous objects will require radar data in order to ensure that they will miss the Earth or, if this is not the case, to determine the exact time and location of the impact. Desirable for this program would be increased access to currently operational planetary radars in California and Puerto Rico, and provision of a suitable southern-hemisphere radar in the future. We anticipate that much of the optical follow-up work can be accomplished with the survey telescopes themselves if they are suitably instrumented, although one or more dedicated follow-up telescopes would greatly improve our ability to study faint and distance asteroids and comets. The survey program also requires rapid international electronic communications and a central organization for coordination of observing programs and maintenance of a database of discovered objects and their orbits.

Expected Survey Results. *Numerical modeling of the operation of the Spaceguard Survey network indicates that as many as a thousand ECAs will be discovered per month. Over a period of two decades we will identify more than 90 percent of potentially threatening ECAs larger than 1 km in diameter, as well as detecting most incoming comets about a year before they approach the Earth. At the same time, tens of thousands of smaller asteroids (down to a few meters in diameter) will also be discovered, although the completeness of the survey declines markedly for objects smaller than about 500 m. The advantage of this survey approach is that it achieves the greatest level of completeness for the largest and most dangerous objects; however, if continued for a long period of time, it will provide the foundation for assessing the risk posed by smaller impacts as well. Continued monitoring of the sky will also be needed to provide an alert for potentially hazardous long-period comets.*

Cost of the Spaceguard Survey. *The survey can begin with current programs in the United States and other countries, which are providing an initial characterization of the ECA population and can serve as a test bed for the technologies proposed for the new and larger survey telescopes. A modest injection of new funds into current programs could also increase current discovery rates by a factor of two or more, as well as provide training for personnel that will be needed to operate the new survey network. For the new telescopes, we assume the use of modern technology that has, over the past decade, substantially reduced the construction costs of telescopes of this aperture. The initial cost to build six 2.5-m telescopes and to establish a center for program coordination is estimated to be about $50M (FY93 dollars), with additional operating expenses for the network of about $10M per year. If construction were begun in FY93,* *the survey could be in operation by about 1997. Over the first decade of operation (to 2007), the survey would require appropriations approaching $100M, perhaps half of which could be provided by the United States and half by international partners.*

Conclusions. *The international survey program described in this report can be thought of as a modest investment to insure our planet against the ultimate catastrophe. The probability of a major impact during the next century is very small, but the consequences of such an impact, especially if the object is larger than about 1 km diameter, are sufficiently terrible to warrant serious consideration. The Spaceguard Survey is an essential step toward a program of risk reduction that can reduce the risk from cosmic impacts by up to 75 percent over the next 25 years.*

1.1 Background

The Earth resides in a swarm of comets and asteroids that can, and do, impact its surface. The solar system contains a long-lived population of asteroids and comets, some fraction of which are perturbed into orbits that cross the orbits of the Earth and other planets. Spacecraft exploration of the terrestrial planets and the satellites of the outer planets has revealed crater-scarred surfaces that testify to a continuing rain of impacting projectiles. Additional evidence concerning cosmic projectiles in near-Earth space has accumulated since the discovery of the first Earth-crossing asteroid nearly sixty years ago, and improvements in telescopic search techniques have resulted in the discovery of dozens of near-Earth asteroids and short period comets each year. The role of impacts in affecting the Earth's geological history, its ecosphere, and the evolution of life itself has become a major topic of current interdisciplinary interest.

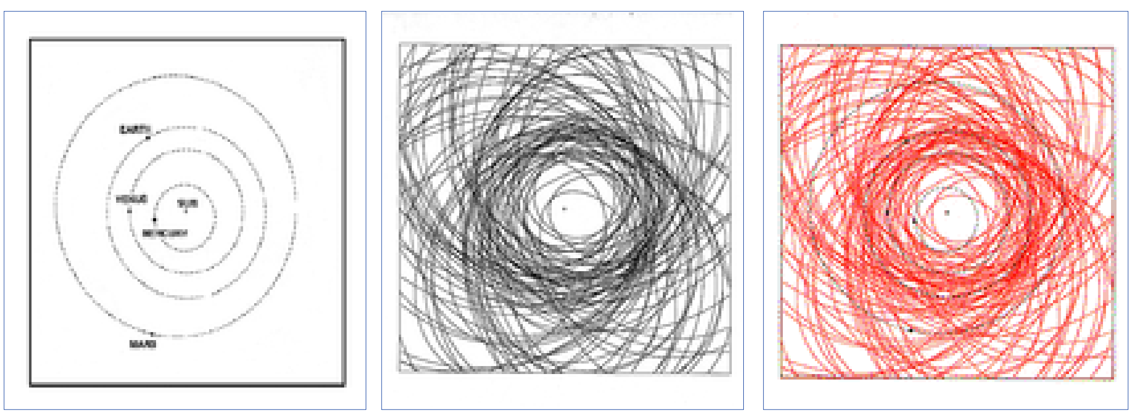

FIGURE 1.1. Earth resides in a swarm of comets and asteroids, as this series of plots graphically shows: (a) the locations of the inner planets an January 1, 1992, (b) the orbits of the 100 largest known near-Earth asteroids, and (c) composite of (a) and (b).
Art courtesy of R. P. Binzel

Significant attention by the scientific community to the hazard began in 1980 when Luis Alvarez and others prposed that such an impact, and the resulting global pall of dust, resulted in the mass extinctions of lifeforms on Earth, ending the age of dinosaurs (Alvarez and others, 1980). Additional papers and discussion in the scientific literature followed, and widespread public interest was aroused. In 1981, NASA organized a workshop "Collision of Asteroids and Comets with the Earth: Physical and Human Consequences" at Snowmass, Colorado (July 13-16, 1981). Asummary of the principal conclusions of the workshop report appeared in the book *Cosmic Catastrophes* (Chapman and Morrison, 1989a) and in a presentation by Chapman and Morrison(1989b) at an American Geophysical Union Natural Hazards Symposium. In response to the close passage of asteroid 1989FC, the American Institute of Aeronautics and Astronautics (AIAA, 1990) recommended studies to increase the detection rate of near-Earth asteroids, and how to prevent such objects striking the Earth. The AIAA brought these recommendations to the attention of the House Committee of Science, Space, and Technology, leading to the Congressional mandate for this workshop included in the NASA 1990 Authorization Bill. In parallel with these political developments, a small group of dedicated observers significantly increased the discovery rate of Near-Earth asteroids and comets, and several of these discoveries were highlighted in the international press. Other recent activity has included the 1991 International Conference on Near-Earth Asteroids (San Juan Capistrano, California, June 30 - July 3), a meeting on the "Asteroid Hazard" held in St. Petersburg, Russia (October 9-10, 1991), and a resolution endorsing international searches for NEO's adopted by the International Astronomical Union (August 1991).

Despite a widespread perception that asteroid impact is a newly recognized hazard, the basic nature of the hazard was roughly understood half a century ago. In 1941, Fletcher Watson published an estimate of the rate of impacts on the Earth, based on the discovery of the first three Earth-approaching asteroids (Apollo, Adonis, and Hermes). A few years later, Ralph Baldwin (1949), in his seminal book The Face of the Moon, wrote

> *...since the Moon has always been the companion of the Earth, the history of the former is only a paraphrase of the history of the latter... [Its mirror on Earth] contains a disturbing factor. There is no assurance that these meteoritic impacts have all been restricted to the past. Indeed we have positive evidence that [sizeable] meteorites and asteroids still abound in space and occasionally come close to the Earth. The explosion that formed the [lunar] crater Tycho...would, anywhere on Earth, be a horrifying thing, almost inconceivable in its monstrosity.*

FIGURE 1.2
. An aerial view of Meteor Crater, Arizona, one of the Earth's youngest impact craters. Field studies indicate that the crater was formed some 50,000 years ago by an iron mass(es) traveling in excess of 11 km/s and releasing 10 to 20 megatons of energy. The result was the formation of a bowl-shaped crater approximately 1 km across and over 200 m deep, surrounded by an extensive ejecta blanket.
Photograph courtesy of R.J. Roddy and K.A. Zeller, U.S. Geological Survey

Watson and Baldwin (both of whom are still alive) were prescient, but in their time few other scientists gave much thought to impacts on the Earth. Recently, however, there has been a gestalt shift that recognizes extraterrestrial impact as a major geological process and, probably, an important influence on the evolution of life on our planet. Also new is our capability to detect such objects and to develop a space technology that could deflect a potential projectile before it struck the Earth.

Chapter 1: Introduction
1.1 | 1.2 | 1.3

1.2 The International NEO Detection Workshop

The United States House of Representatives, in its NASA Multiyear Authorization Act of 1990 (26 September 1990), included the following language:

> *"The Committee believes that it is imperative that the detection rate of Earth-orbit-crossing asteroids must be increased substantially, and that the means to destroy or alter the orbits of*

asteroids when they threaten collision should be defined and agreed upon internationally.

"The chances of the Earth being struck by a large asteroid are extremely small, but since the consequences of such a collision are extremely large, the Committee believes it is only prudent to assess the nature of the threat and prepare to deal with it. We have the technology to detect such asteroids and to prevent their collision with the Earth.

"The Committee therefore directs that NASA undertake two workshop studies. The first would define a program for dramatically increasing the detection rate of Earth-orbit-crossing asteroids; this study would address the costs, schedule, technology, and equipment required for precise definition of the orbits of such bodies. The second study would define systems and technologies to alter the orbits of such asteroids or to destroy them if they should pose a danger of life on Earth. The Committee recommends international participation in these studies and suggests that they be conducted within a year of the passage of this legislation."

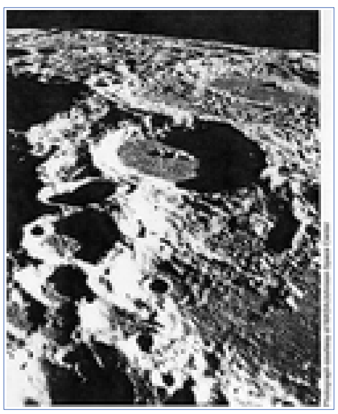

FIGURE 1.3. The heavily cratered highlands of the Moon record the period of heavy bombardment that marked the first 500 million years of lunar history.
Photograph courtesy of NASA Johnson Space Center

The present report of the NASA International Near-Earth Object Detection Workshop is the direct result of this Congressional request to NASA. A second NASA workshop on the question of altering asteroid orbits is scheduled for 1992.

The NASA International Near-Earth Object Detection Workshop was organized in the spring of 1991 and held three formal meetings: on June 30 - July 3 at the San Juan Capistrano Research Institute, on

September 24-25 at the NASA Ames Research Center, and on November 5 in Palo Alto, California. The group has the following membership of 24 individuals from four continents.

- Richard Binzel (Massachusetts Institute of Technology, USA)
- Edward Bowell (Lowell Observatory, USA)
- Clark Chapman (Planetary Science Institute, USA)
- Louis Friedman (The Planetary Society, USA)
- Tom Gehrels (University of Arizona, USA)
- Eleanor Helin (Caltech/NASA Jet Propulsion Laboratory, USA)
- Brian Marsden (Harvard/Smithsonian Center for Astrophysics, USA)
- Alain Maury (Observatoire de la Cote d'Azur, France)
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- John Pike (Federation of American Scientists, USA)
- Jurgen Rahe (NASA Headquarters, USA)
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- Donald Yeomans (Caltech/NASA Jet Propulsion Laboratory, USA)

1.3 Approach to the Problem

As described in the following chapters of this report, the workshop group has analyzed the nature of the hazard and defined a practical program for the detection of potentially catastrophic impacts. The greatest risk is from the impact of the largest objects -- those with diameters greater than 1 km. Such impacts, which occur on average from once to several times per million years, are qualitatively as well as quantitatively different from any other natural disasters in that their consequences are global, affecting the entire planet. How, then, should we approach the problem of discovering and tracking these objects?

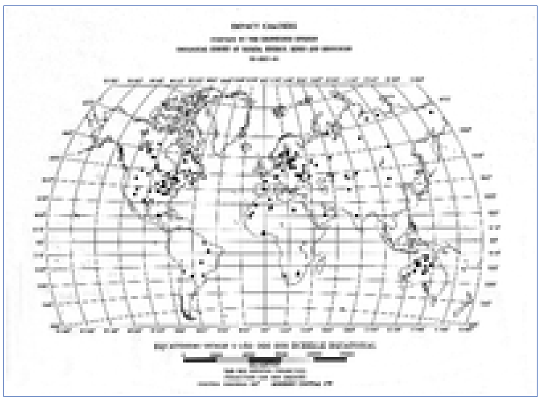


FIGURE 1.4. Approximately 130 terrestrial impact craters have been identified. They range up to 140 to 200 km in diameter and from recent to about two billion years in age. More craters have been identified in Australia, North America, and eastern Europe partly because these areas have been relatively stable for considerable geologic periods, thus preserving the early geologic record, and because active search programs have been conducted in these areas.

Art courtesy of R.A.F. Grieve, Geological Survey of Canada

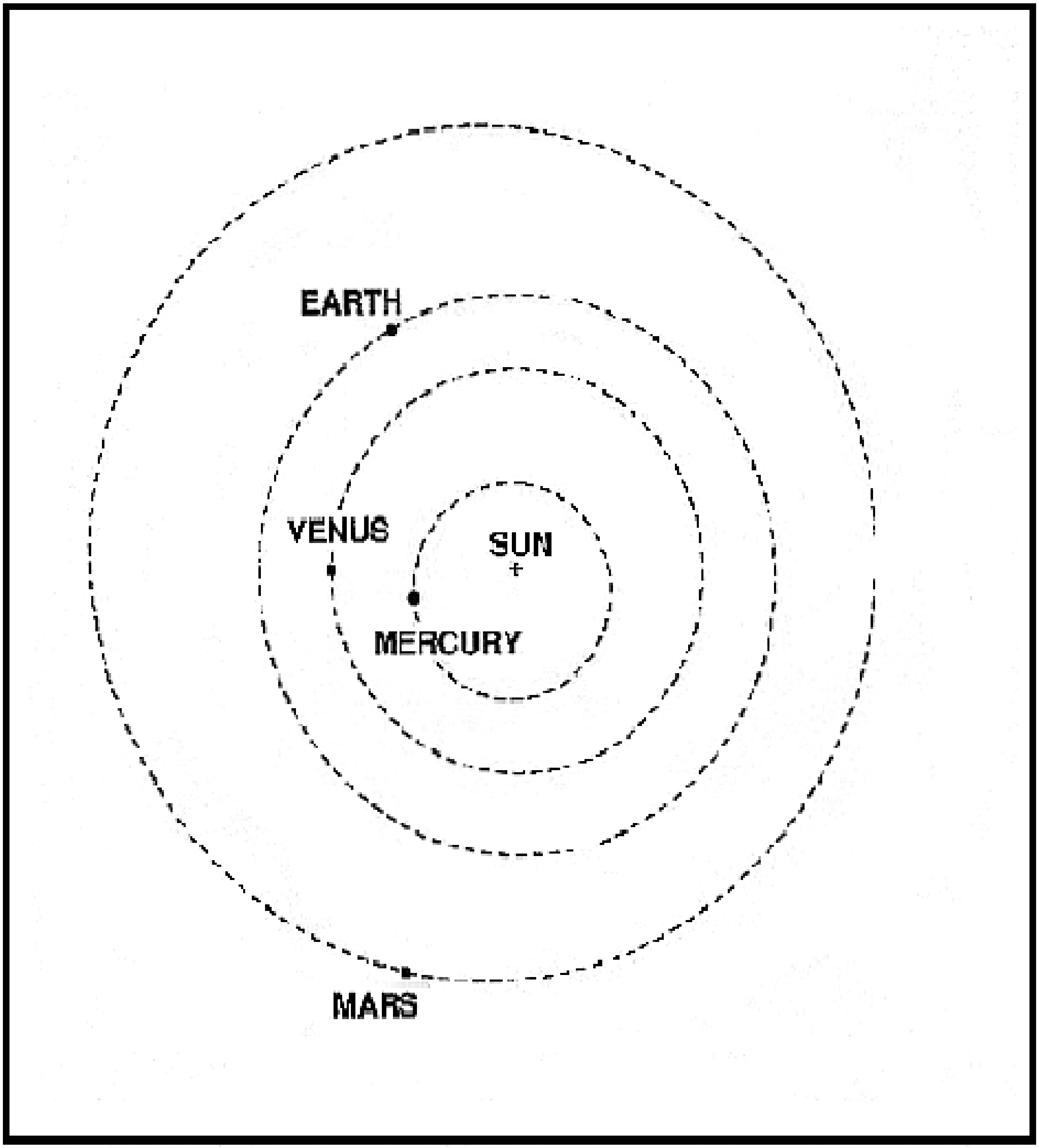
About 90 percent of the potential Earth-impacting projectiles are near-Earth asteroids or short-period comets, called collectively NEOs (Near Earth Objects). The other 10 percent are intermediate or long-period comets (those with periods longer than 20 years), which are treated separately since they they spend so little time in near-Earth space. The NEOs have orbits that closely approach or intersect that of the Earth. Their normal orbital motion brings them relatively near the Earth at intervals of a few years, permitting their discovery. The objective of an NEO survey is to find these objects during their periodic approaches to the Earth, to calculate their long-term orbital trajectories, and to identify any that may impact the

Earth over the next several centuries. If any appear to be on Earth-impact trajectories, there will generally be a period of at least several decades during which to take corrective action. It should be emphasized that we are not discussing either a short-range search nor a quick-response defense system. The chance that an NEO will be discovered less than a few years before impact is vanishingly small. The nature of the NEO orbits allows us to carry out a deliberate, comprehensive survey with ample time to react if any threatening NEO is found. In contrast, however, the warning time for impact from a long-period comet might be as short as two years, requiring a different class of response.

In order to carry out a deliberate and comprehensive search, we must detect, over a period of a decade or more, the NEOs larger than our 1-km size threshold that pass near the Earth. This requires that we monitor a region of space extending outward from the orbit of the Earth approximately as far as the inner edge of the main asteroid belt, at a distance of 200 million kilometers. The easiest way to detect these NEOs is by observing their reflected sunlight, although they can also be seen in the infrared using their emitted thermal radiation. More exotic technologies are not appropriate; radar, in particular, is limited to targets close to the Earth, and so is unsuitable to a survey extending 200 million kilometers into space. In principle, the survey could be carried out either from the ground or from orbit. The brightness of a 1-km NEO at 200 million kilometers, assuming a reflectivity of 3 percent or more, corresponds to stellar magnitude 22. Although they are quite faint, such objects are readily detectable with conventional ground-based telescopes and can be distinguished from background stars by their characteristic motion. Thus there is no requirement for a more expensive space-based system. This brightness limit also determines the minimum telescope aperture of about 2 m that is required for a complete survey. Thus we have it within our current capability to construct a network of survey telescopes at relatively modest cost that can discover and track essentially all of the NEOs greater than 1 km in diameter. In addition, this same network of optical survey telescopes will be capable of detecting most incoming intermediate- or long-period comets and determining if any of them is has the potential to strike the Earth. However, the time between detection and possible impact will be much shorter for the long-period comets, probably no more than two years.

The survey program described in this report has the potential to alter fundamentally the way we view the threat of cosmic impacts. To date we have talked about a relatively undefined threat, to be discussed in terms of probabilities or statistical risks. While we know that such impacts must take place from time to time, we do not know if there are any specific bodies in space might impact the Earth over the next few centuries. If this search program is carried out, however, we can answer this question to at least the 75 percent confidence level. If such an object is found, then we can turn our attention to dealing with the threat it poses. In other words, we have the capability for at least a 75 percent reduction in the hazard posed by cosmic impacts.

Next Chapter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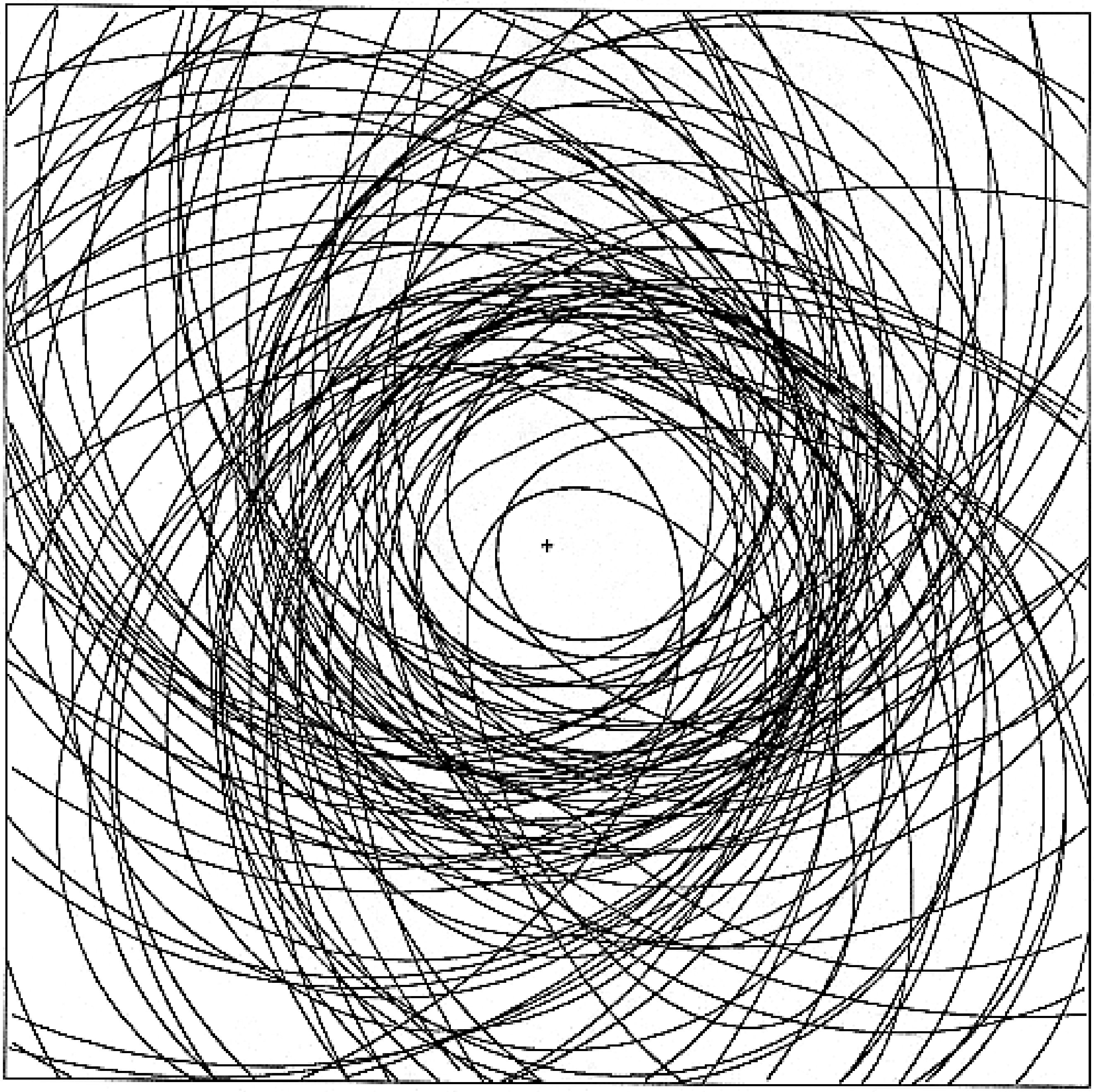

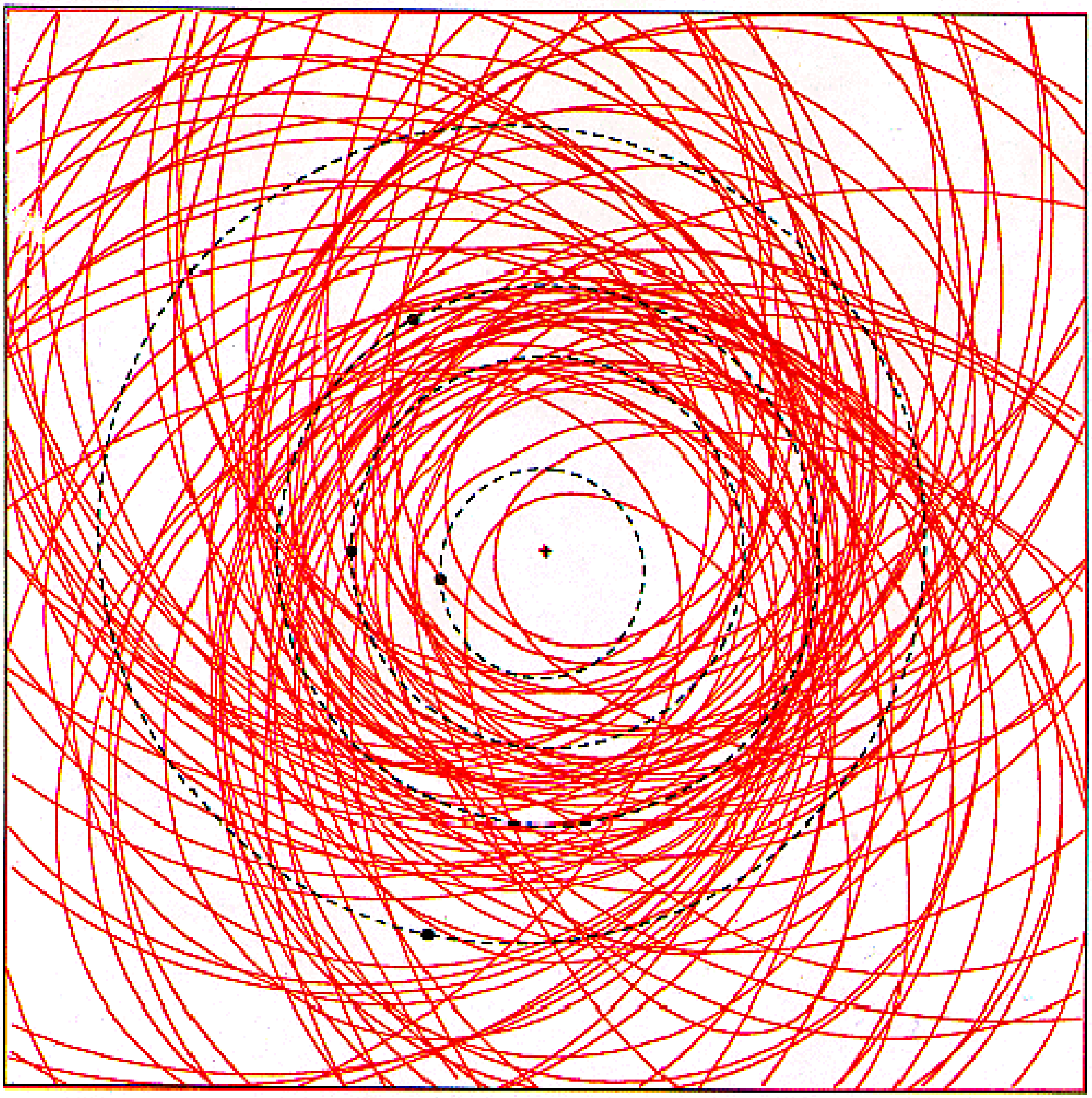

Photograph courtesy of NASA/Johnson Space Center

IMPACT CRATERS

COMPILED BY THE GEOPHYSICS DIVISION

GEOLOGICAL SURVEY OF CANADA, ENERGY, MINES AND RESOURCES

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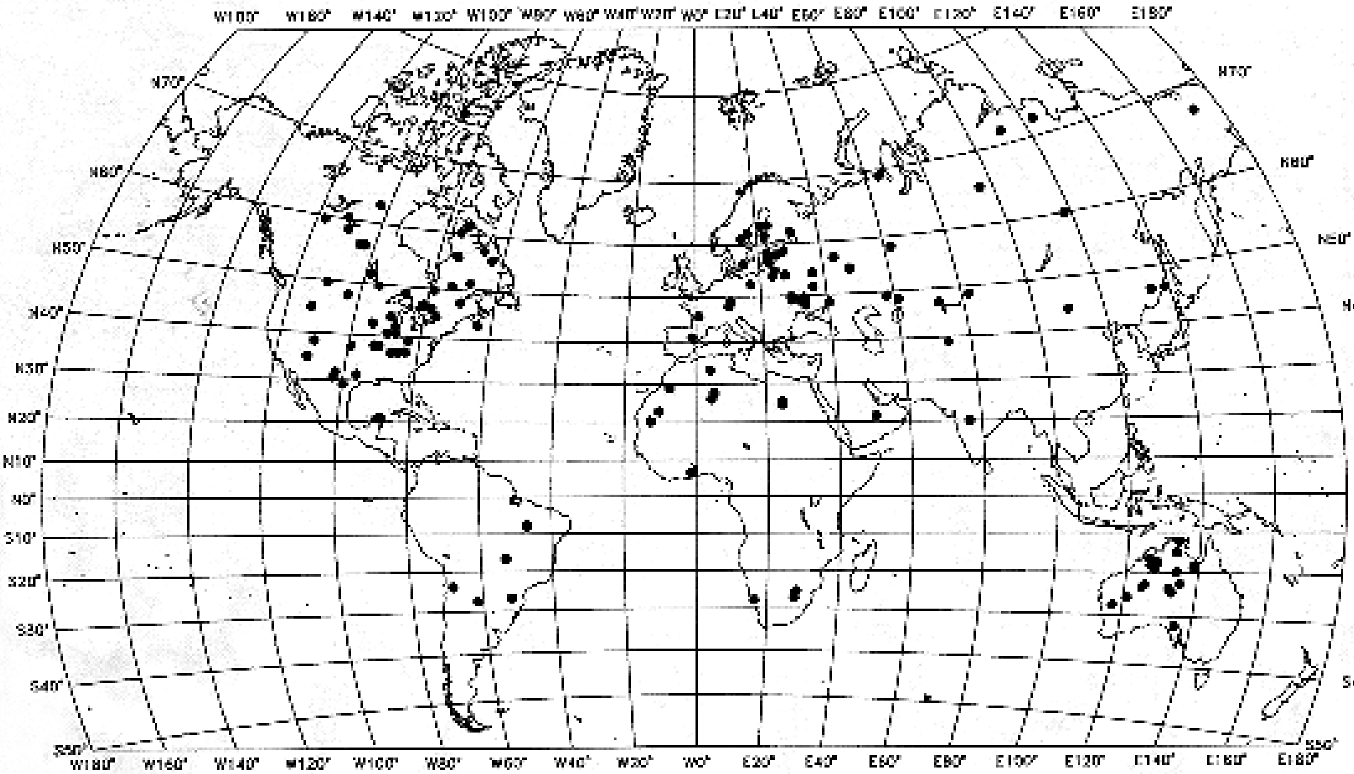

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2.1 Introduction

Throughout Its history, the Earth has been impacted by countless asteroids and comets. Smaller debris continually strike Earth's upper atmosphere where they burn due to friction with the air; meteors (which are typically no larger than a pea and have masses of about a gram) can be seen every night from a dark location if the sky is clear. Thousands of meteorites (typically a few kilograms in mass) penetrate the atmosphere and fall harmlessly to the ground each year. On rare occasions, a meteorite penetrates the roof of a building, although to date there are no fully documented human fatalities. A much larger event, however, occurred in 1908 when a cosmic fragment disintegrated in the atmosphere over Tunguska, Siberia, with an explosive energy of more than 10 megatons TNT. But even the Tunguska impactor was merely one of the smallest of Earth's neighbors in space. Of primary concern are the larger objects, at least one kilometer in diameter. Although very rare, the impacts of these larger objects are capable of severely damaging the Earth's ecosystem with a resultant massive loss of life.

In the following discussion, we examine the risks posed by impacting objects of various sizes. These projectiles could be either cometary or asteroidal. In terms of the damage they do, it matters little whether they would be called comets or asteroids by astronomical observers. We term these objects collectively NEOs (Near Earth Objects).

Every few centuries the Earth is struck by an NEO large enough to cause thousands of deaths, or hundreds of thousands of deaths if it were to strike in an urban area. On time scales of millennia, impacts large enough to cause damage comparable to the greatest known natural disasters may be expected to occur (Pike 1991). Indeed, during our lifetime, there is a small but non-zero chance (very roughly 1 in 10,000) that the Earth will be struck by an object large enough to destroy food crops on a global scale and possibly end civilization as we know it (Shoemaker and others 1990).

As described in Chapter 3, estimates of the population of NEOs large enough to pose a global hazard are reliable to within a factor of two, although estimates of the numbers of smaller objects are more uncertain. Particularly uncertain is the significance of hard-to-detect long-period or new comets, which would generally strike at higher velocities than other NEO's (Olsson-Steel 1987), although asteroids (including dead comets) are believed to dominate the flux. However, the resulting environmental consequences of the impacts of these objects are much less well understood. The greatest uncertainty in comparing the impact hazard with other natural hazards relates to the economic and social consequences of impacts. Little work has been done on this problem, but we summarize the consequences -- to the degree they are understood -- in this chapter.

2.2 The Relationship of Risk to Size of Impactor

Small impacting objects that produce ordinary meteors or fireballs dissipate their energy in the upper atmosphere and have no direct effect on the ground below. Only when the incoming projectile is larger than about 10 m diameter does it begin to pose some hazard to humans. The hazard can be conveniently divided into three broad categories that depend on the size or kinetic energy of the impactor:

1. Impacting body generally is disrupted before it reaches the surface; most of its kinetic energy is dissipated in the atmosphere, resulting in chiefly local effects.
2. Impacting body reaches ground sufficiently intact to make a crater; effects are still chiefly local, although nitric oxide and dust can be carried large distances, and there will be a tsunami if the impact is in the ocean.
3. Large crater-forming impact generates sufficient globally dispersed dust to produce a significant, short-term change in climate, in addition to devastating blast effects in the region of impact.

FIGURE 2.1. ***On August 10, 1972, an alert photographer in Grand Teton National Park recorded the passage of an object estimated at 10 m diameter and weighing several thousand tons. The object narrowly missed colliding with Earth's surface, although it burned in our atmosphere for 101 seconds as it travelled over 1,475 km at about 15 km/s.***

Photograph by James M. Baker, courtesy of Dennis Milon.

The threshold size of an impacting body for each category depends on its density, strength, and velocity as well as on the nature of the target. The threshold for global effects, in particular, is not well determined.

Category 1: 10-m to 100-m diameter impactors

Bodies near the small end of this size range intercept Earth every decade. Bodies about 100 m diameter and larger strike, on average, several times per millennium. The kinetic energy of a 10-m projectile traveling at a typical atmospheric entry velocity of 20 km/s is about 100 kilotons TNT equivalent, equal to several Hiroshima-size bombs. The kinetic energy of a 100-m diameter body is equivalent to the explosive energy of about 100 megatons, comparable to the yield of the very largest thermonuclear devices.

For the 10-m projectiles, only rare iron or stony-iron projectiles reach the ground with a sufficient fraction of their entry velocity to produce craters, as happened in the Sikhote-Alin region of Siberia in 1947. Stony bodies are crushed and fragmented during atmospheric deceleration, and the resulting fragments are quickly slowed to free-fall velocity, while the kinetic energy is transferred to an atmospheric shock wave. Part of the shock wave energy is released in a burst of light and heat (called a meteoritic fireball) and part is transported in a mechanical wave. Generally, these 100-kiloton disruptions occur high enough in the atmosphere so that no damage occurs on the ground, although the fireball can attract attention from distances of 600 km or more and the shock wave can be heard and even felt on the ground.

With increasing size, asteroidal projectiles reach progressively lower levels in the atmosphere before disruption, and the energy transferred to the shock wave is correspondingly greater. There is a threshold where both the radiated energy from the shock and the pressure in the shock wave can produce damage. A historical example is the Tunguska event of 1908, when a body perhaps 60 m in diameter was disrupted in the atmosphere at an altitude of about 8 km. The energy released was about 12 megatons, as estimated from airwaves recorded on meteorological barographs in England, or perhaps 20 megatons as estimated from the radius of destruction. Siberian forest trees were mostly knocked to the ground out to distances of about 20 km from the end point of the fireball trajectory, and some were snapped off or knocked over at distances as great as 40 km. Circumstantial evidence suggests that fires were ignited up to 15 km from the endpoint by the intense burst of radiant energy. The combined effects were similar to those expected from a nuclear detonation at a similar altitude, except, of course, that there were no accompanying bursts of neutrons or gamma rays nor any lingering radioactivity. Should a Tunguska-like event happen over a densely populated area today, the resulting airburst would be like that of a 10-20 megaton bomb: buildings would be flattened over an area 20 km in radius, and exposed flammable materials would be ignited near the center of the devastated region.

An associated hazard from such a Tunguska-like phenomenon is the possibility that it might be misinterpreted as the explosion of an actual nuclear weapon, particularly if it were to occur in a region of the world where tensions were already high. Although it is expected that sophisticated nuclear powers would not respond automatically to such an event, the possible misinterpretation of such a natural event dramatizes the need for heightening public consciousness around the world about the nature of unusually bright fireballs.

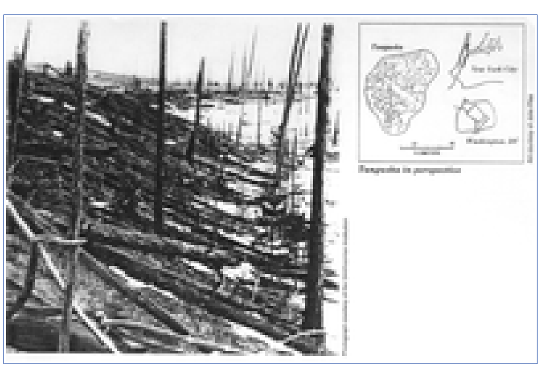


FIGURE 2.2. ***On June 30, 1908, at 7:40 AM, a cosmic projectile exploded in the sky over Siberia. It flattened 2,000 square kilometers of forest in the Tunguska region. If a similar event were to occur today, hundreds of thousands of people would be killed, and damage would be measured in hundreds of billions of dollars.*** Photograph courtesy of Smithsonian Institution, Art courtesy of John Pike

Category 2: 100-m to 1-km diameter impactors

Incoming asteroids of stony or metallic composition that are larger than 100 m in diameter may reach the ground intact and produce a crater. The threshold size depends on the density of the impactor and its speed and angle of entry into the atmosphere. Evidence from the geologic record of impact craters as well as theory suggests that, in the average case, stony objects greater than 150 m in diameter form craters. They strike the Earth about once per 5000 years and -- if impacting on land -- produce craters about 3 km in diameter. A continuous blanket of material ejected from such craters covers an area about 10 km in diameter. The zone of destruction extends well beyond this area, where buildings would be damaged or flattened by the atmospheric shock, and along particular directions (rays) by flying debris. The total area of destruction is not, however, necessarily greater than in the case of atmospheric disruption of somewhat smaller objects, because much of the energy of the impactor is absorbed by the ground during crater formation. Thus the effects of small crater-forming events are still chiefly local.

Toward the upper end of this size range, the megaton equivalent energy would so vastly exceed what has been studied in nuclear war scenarios that it is difficult to be certain of the effects. Extrapolation from smaller yields suggests that the "local" zones of damage from the impact of a 1-km object could envelop whole states or countries, with fatalities of tens of millions in a densely populated region. There would also begin to be noticeable global consequences, including alterations in atmospheric chemistry and cooling due to atmospheric dust -- perhaps analogous to the "year without a summer" in 1817, following the explosion of the volcano Tambora.

Comets are composed in large part of water ice and other volatiles and therefore are more easily fragmented than rocky or metallic asteroids. In the size range from 100 m to 1 km, a comet probably cannot survive passage through the atmosphere, although it may generate atmospheric bursts sufficient to produce local destruction.

This is a subject that needs additional study, requiring a better knowledge of the physical nature of comets.

Category 3: 1 km to 5 km diameter impactors

At these larger sizes, a threshold is finally reached at which the impact has serious global consequences, although much work remains to be done to fully understand the physical and chemical effects of material injected into the atmosphere. In general, the crater produced by these impacts has 10 to 15 times the diameter of the projectile; i.e., 10-15 km diameter for a 1-km asteroid. Such craters are formed on the continents about once per 300,000 years. At impactor sizes greater than 1 km, the primary hazard derives from the global veil of dust injected into the stratosphere. The severity of the global effects of large impacts increases with the size of the impactor and the resulting quantity of injected dust. At some size, an impact would lead to massive world-wide crop failures and might threaten the survival of civilization. At still larger sizes, even the survival of the human species would be put at risk.

What happens when an object several kilometers in diameter strikes the Earth at a speed of tens of kilometers per second? Primarily there is a massive explosion, sufficient to fragment and partially vaporize both the projectile and the target area. Meteoric phenomena associated with high speed ejecta could subject plants and animals to scorching heat for about half an hour, and a global firestorm might them ensue. Dust thrown up from a very large crater would lead to total darkness over the whole Earth, which might persist for several months. Temperatures could drop as much as tens of degrees C. Nitric acid, produced from the burning of atmospheric nitrogen in the impact fireball, would acidify lakes, soils, streams, and perhaps the surface layer of the oceans. Months later, after the atmosphere had cleared, water vapor and carbon dioxide released to the stratosphere would produce an enhanced greenhouse effect, possibly raising global temperatures by as much as ten degrees C above the pre-existing ambient temperatures. This global warming might last for decades, as there are several positive feedbacks; warming of the surface increases the humidity of the troposphere thereby increasing the greenhouse effect, and warming of the ocean surface releases carbon dioxide which also increases the greenhouse effect. Both the initial months of darkness and cold, and then the following years of enhanced temperatures, would severely stress the environment and would lead to drastic population reductions of both terrestrial and marine life.

2.3 Threshold Size for Global Catastrophe

The threshold size of impactor that would produce one or all of the effects discussed above is not accurately known. The geochemical and paleontological record has demonstrated that one impact (or perhaps several closely spaced impacts) 65 million years ago of a 10-km NEO resulted in total extinction of about half the living species of animals and plants (figure 2.3) (Sharpton and Ward, 1990). This so-called K-T impact may have exceeded 100 megatons in explosive energy. Such mass extinctions of species have recurred several times in the past few hundred million years; it has been suggested, although not yet proven, that impacts are responsible for most such extinction events. We know from astronomical and geological evidence that impacts of objects with diameters of 5 km or greater occur about once every 10 to 30 million years.

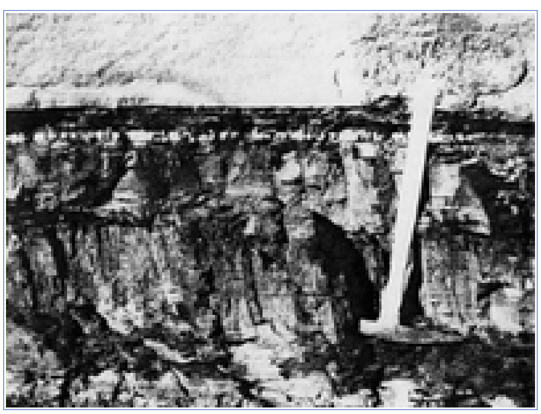


FIGURE 2.3. ***A thin, bright layer of clay less than an inch wide (toward the end of the rock-hammer handle, separated from the thick bright sandstone by a narrow seam of coal) marks debris from the catastrophic event that ended the Cretaceous era 65 million years ago. Here the boundary is shown in an outcrop near Madrid, Colorado.*** Photograph by Alan Hildebrand

Death by starvation of much of the world's population could result from a global catastrophe far less horrendous than those cataclysmic impacts that would suddenly render a significant fraction of species actually extinct, but we know only very poorly what size impact would cause such mortality. In addition to all of the known variables (site of impact, time of year) and the uncertainties in physical and ecological consequences, there is the question of how resilient our agriculture, commerce, economy, and societal organization might prove to be in the face of such an unprecedented catastrophe.

These uncertainties could be expressed either as a wide range of possible consequences for a particular size (or energy) of impactor or as a range of impactor sizes that might produce a certain scale of global catastrophe. We take the second approach and express the uncertainty as a range of threshold impactor sizes that would yield a global catastrophe of the following proportions:

- It would destroy most of the world's food crops for a year, and /or
- It would result in the deaths of more than a quarter of the world's population, and/or
- It would have effects on the global climate similer to those calculated for "nuclear winter", and/or
- It would threaten the stability and future of modern civilization.

A catastrophe having one, or all, of these traits would be a horrifying thing, unprecedented in history, with potential implications for generations to come.

To appreciate the scale of global catastrophe that we have defined, it is important to be clear what is not. We are talking about a catastrophe far larger than the effects of the great World Wars; it would result from an impact explosion certainly larger than if 100 of the very biggest Hydrogen bombs ever tested were detonated at once. On the other hand, we are talking about an explosion far smaller (less than 1 percent of the energy) the the K-T impact 65 million years ago. We mean a catastrophe that would threaten modern civilization, not an apocalypse that would threaten the survival of the human species.

What is the range of impactor sizes that might lead to this magnitude of global catastrophe? At the July 1991 Near-Earth Asteroid Conference in San Jaun Capistrano, California, the most frequently discussed estimate of the threshold impactor diameter for globally catstrphic effects was about 2 km. An estimate of the threshold size was derived for this Workshop in September 1991 by Brian Toon, of NASA Ames Research Center. Of the various enviromental effects of a large impact, Toon believes that the greatest harm would be done by the sub-micrometer dust launced into the stratosphere. The very fine dust has a long residence time, and global climate modeling studies by Covey and others (1990) imply significant drops in global temperature that would threaten agriculture worldwide. The quanity of sub-micrometer dust required for climate effects equivalent to those calculated for nuclear winter is estimated at about 10,000 Teragrams (Tg) (1 Tg = 10^{12}g). For a 30 km/s impact, this translate to a threshold impacting body diameter of between 1 and 1.5 km diameter.

The threshold for an impact that causes widespread global mortality and threatens civilization almost certainly lies between about 0.5 and 5 km diameter, perhaps near 2 km. Impacts of objects this large occur from one to several times per million years.

2.4 Risk Analysis

If this estimate of the frequency of threshold impact is correct, then the chances of an asteroid catastrophe happening in the near future -- while very low -- is greater than the probablility of other threats to life that our society takes very seriously. For purposes of discussion, we adopt the once-in-500,000 year estimate for the globally catastrophic impact. It is important to keep in mind that the frequency could be greater than this, although probably not by more than a factor of two. The frequency could equally well be a factor of ten smaller.

Because the risk of such an impact happening in the near future is very low, the nature of the impact hazard is unique in our experience. Nearly all hazards we face in life actually happen to someone we know, or we learn about them from the media, whereas no large impact has taken place within the total span of human history. (If such an event took place before the dawn of history roughly 10,000 years ago there would be no record of the event, since we are not postulating an impact large enough to produce a mass extinction that would be readily visible in the fossil record). But also in contrast to more familiar disasters, the postulated impact would produce devastation on a global scale. Natural disasters, including tornadoes and cyclones, earthquakes, tsunamis, volcanic eruptions, firestorms, and floods often kill thousands of people, and occasionally several million. But the civilization-destroying impact exceeds all of these other disasters in that it could kill a billion or more people, leading to as large a percentage loss of life worldwide as that experienced by Europe from the Black Death in the 14th century. It is this juxtaposition of the small probability of occurrence balanced against the enormous consequences if it does happen that makes the impact hazard such a difficult and controversial topic.

Frequency of Impacts of different sizes

We begin to address the risk of cosmic impacts by looking at the frequency of events of different magnitudes. Small impacts are much more frequent than large ones, as is shown in Figure 2.4. This figure illustrates the average interval between impacts as a function of energy, as derived from the lunar cratering record and other astronomical evidence. For purposes of discussion , we consider two cases: The threshold globally catastrophic impact discussed above, and for comparison, a Tunguska-class impact from a smaller object perhaps 100 m in diameter. In all of the examples given below, the numbers are approximate and are used only to illustrate the general magnitudes involved.

For the globally catastrophic impact:

- Average interval between impacts: 500,000 years

For the Tunguska-class impacts:

- Average interval between impacts for total Earth: 300 years
- Average interval between impacts for populated area of Earth: 3,000 years
- Average interval between impacts for world urban areas: 100,000 years
- Average interval between impacts for U.S. urban areas only: 1,000,000 years

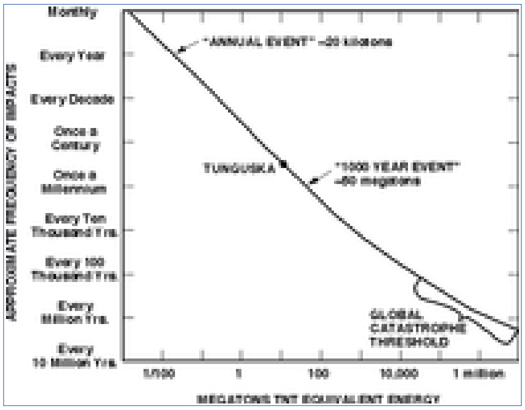


FIGURE 2.4. ***Estimated frequency of impacts on the Earth from the present population of comets and asteroids, and evidence from lunar craters. The megaton equivalents of energy are shown, as are possible and nearly certain thresholds for global catastrophe. (based on Shoemaker 1983)***

We see from this simple calculation that even for a large country such as the U.S., the Tunguska-class impacts on urban areas occur less often than the globally catastrophic impact, emphasizing the fact that the large impacts dominate the risk. This point is also made in Figure 2.5, which plots the expected fatalities per event as a function of diameter (and energy) of the impacting object. The figure shows schematically the transition in expected fatalities per impact event that takes place as the global threshold is reached for objects between 0.5 and 5 kilometers in diameter.

Annual risk of death from impacts

One way to address the risk is to express that risk in terms of the annual probability that an individual will be killed as a result of an impact. This annual probability of mortality is the product of (a) the probability that the impact will occur and (b) the probability that such an event will cause the death of any random individual.

For the globally catastrophic impact:

- Average interval between impacts for total Earth: 500,000 years
- Annual probability of impact: 1/500,000
- Assumed fatalities from impact: one-quarter of world population
- Probability of death for an individual: 1/4
- Annual probability of an individuals death: 1/2,000,000

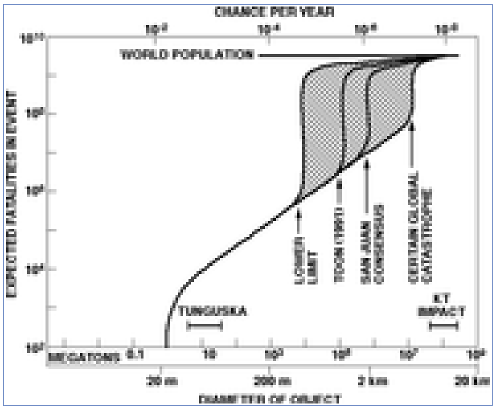


FIGURE 2.5. ***Large impacts dominate the risk, as seen in this schematic indication of expected fatalities per event as a function of diameter (and energy) of the impacting object. (C. Chapman)***

For the Tunguska-class impact:

- Average interval between impacts for total Earth: 300 years
- Assumed area of devastation and total mortality from impact: 5,000 sq km (1/10,000 of Earth's surface)
- Annual probability of an individual's death: 1/30,000,000

Thus we see that the annualized risk is about 15 times greater from the large impact than from the Tunguska-class impact.

Equivalent annual deaths as a measure of risk

An alternative but equivalent way to express the risks is in terms of average annual fatalities. While such an index is convenient for comparison with other risks, we stress the artificiality of applying this approach to the very rare impact catastrophes. The concept of equivalent annual deaths strictly applies only in a static world in which the population and the mortality rate from other causes do not vary with time. This figure is obtained by multiplying the population of the Earth by the total annual probability of death calculated above. In the case of the U.S equivalent deaths, we allow for the higher than average population density in the U.S.

For the globally catastrophic impact:

- Total annual probability of death: 1/2,000,000
- Equivalent annual deaths for U.S. population only: 125
- Equivalent annual deaths (worldwide population):2,500

For the Tunguska-class impact:

- Total annual probability of death: 1/30,000,000
- Equivalent annual deaths for U.S. population only: 15
- Equivalent annual deaths (worldwide population): 150

These figures can be compared with the mortality rates from other natural and man-made causes to obtain a very rough index of the magnitude of the impact-catastrophe hazard. For example, the U.S. numbers can be compared with such other causes of death as food poisoning by botulism (a few per year), tornadoes (100 per year), and auto accidents (50,000 per year).

Qualitative difference for the impact catastrophe

The above analysis is presented to facilitate comparison of impact hazards with others with which we may be more familiar. However, there is a major *qualitative* difference between impact catastrophes and other more common natural disasters. A global impact catastrophe could lead to a billion or more fatalities and an end to the world as we know it. No other natural disasters, including the Tunguska-class impacts, have this nature. They represent just one among many causes of human death. In contrast, the potential consequences of a large impact set it apart from any other phenomenon with the exception of full-scale nuclear war.

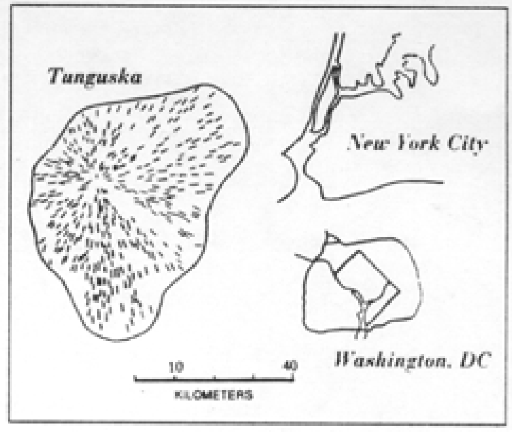
2.5 Conclusions

The greatest risk from cosmic impacts is associated with asteroids a few kilometers in diameter; such an impact would produce an environmental catastrophe that could lead to billions of fatalities. We do not know the threshold diameter at which the impact effects take on this global character, but it is probably near 2 km, and it is unlikely to be less than 1 km. As a first step toward significant reduction of this hazard, we need to identify potential asteroidal impactors larger than 1 km diameter. In addition, attention should be given to the inherently more difficult problem of surveying as many potential "new" cometary impactors of similar equivalent energy as is practical. As noted in Chapter 5, the comets account for 5-10 percent of impactors in this size range. However, because of their greater impact speeds, these comets could contribute as much as 25 percent of the the craters larger than 20 km in diameter.

Finally, because of the higher frequency and nonetheless significant consequences of impact of objects with diameters in the range of 100 m to 1 km, the survey should include bodies in this size range as well. There are wide differences among people in their response to hazards of various types. We have concentrated on the globally catastrophic case because of its qualitatively dreadful nature. But some people consider the threat of the more frequent Tunguska-like events to be more relevant to their concerns, even though the objective hazard to human life is much less. In order to protect against such events (or at least mitigate their effects), impactors as small as 100 m diameter would need to be located with adequate warning before impact to destroy them or at least evacuate local populations. Fortunately, as will be described in Chapter 7, the survey network designed to detect and track the larger asteroids and comets will also discover tens of thousands of Earth-approaching objects in the 100-m to 1-km size range.

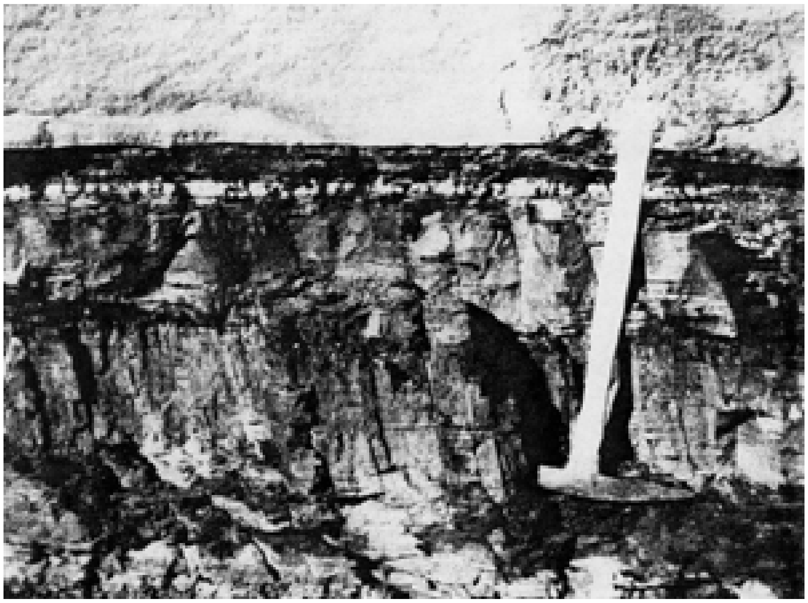
Next Chapter

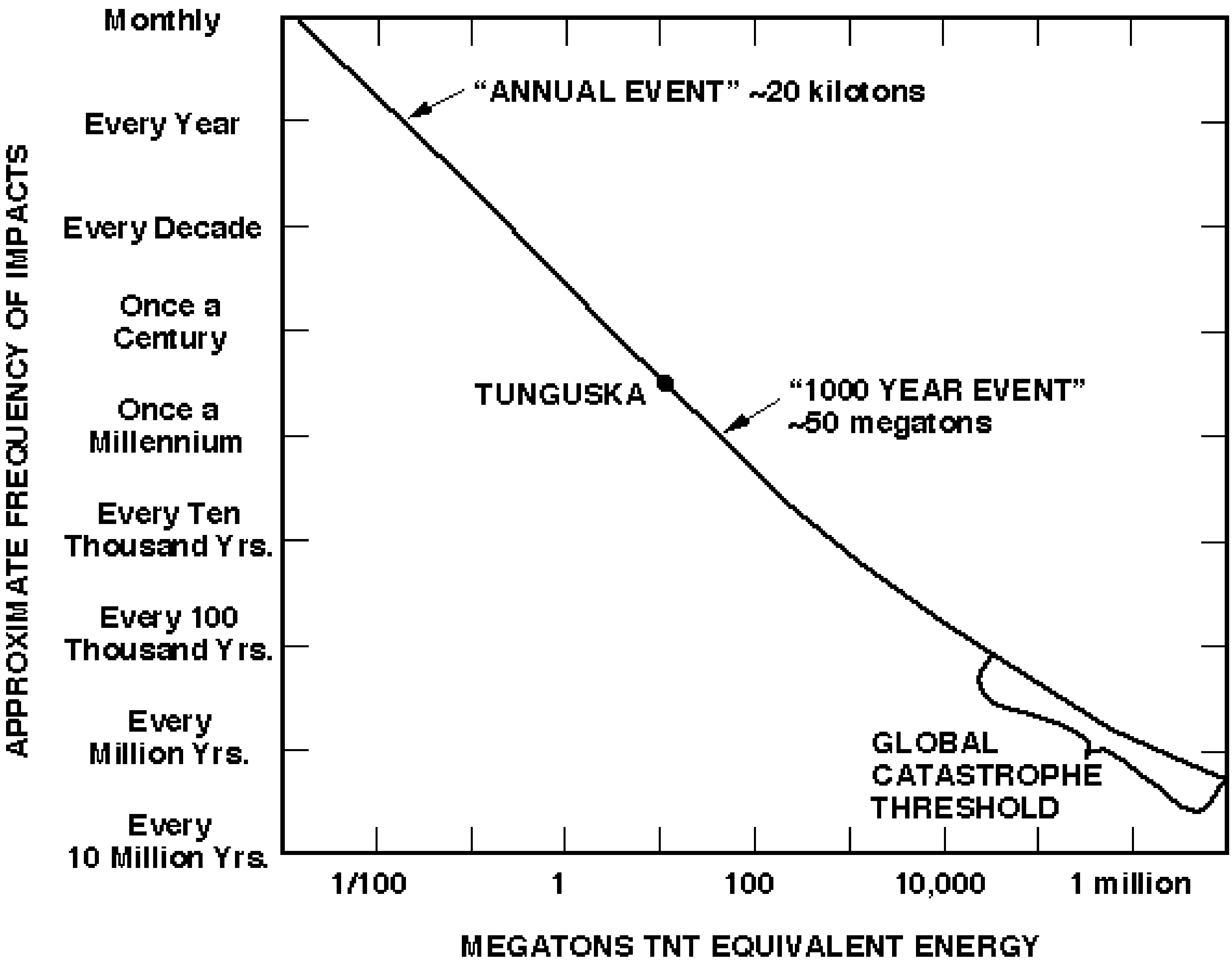
Photograph courtesy of the Smithsonian Institution



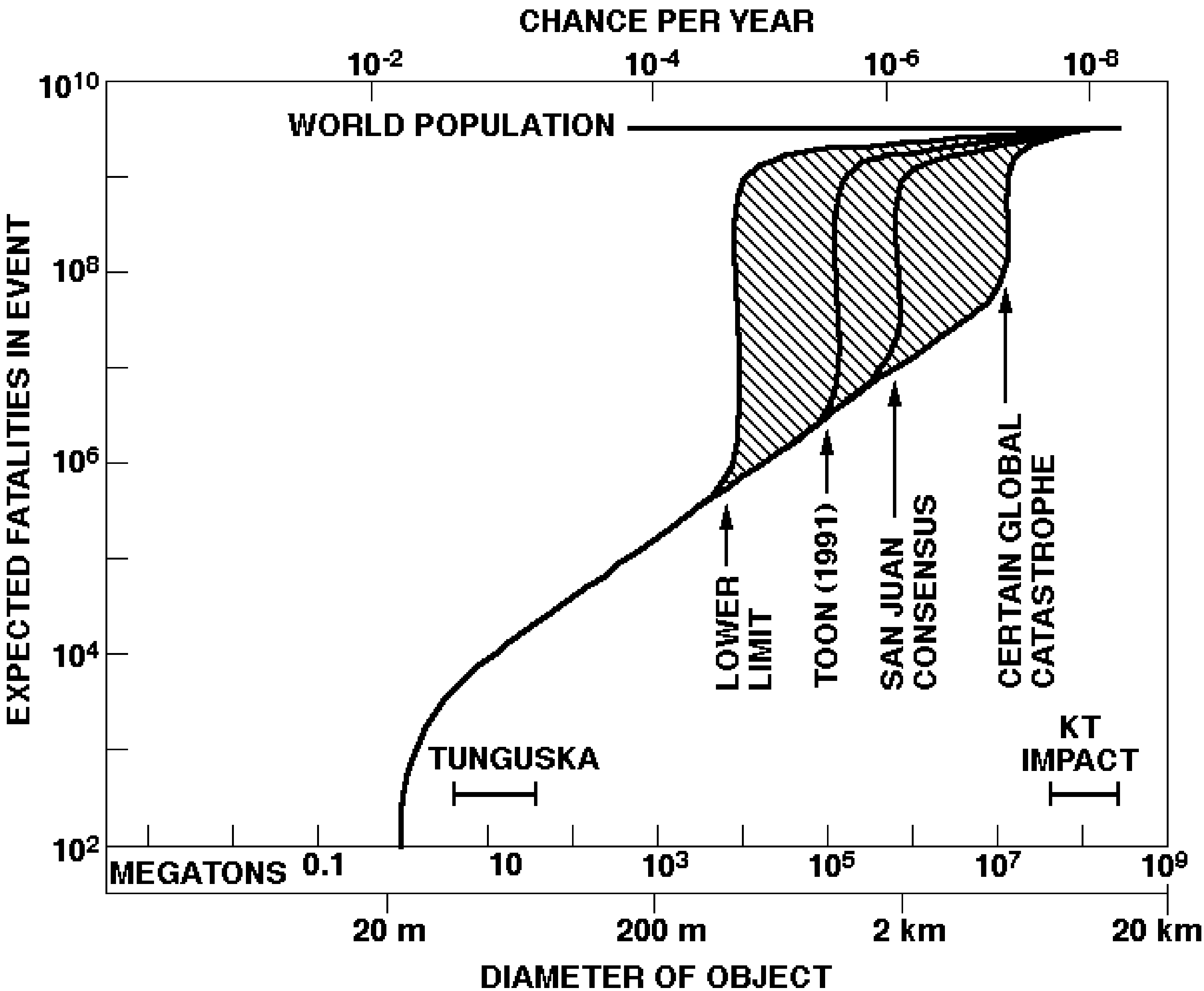
Art courtesy of John Pike

Tunguska in perspective





APPROXIMATE FREQUENCY OF IMPACTS
Monthly
Every Year
Every Decade
Once a Century
Once a Millennium
Every Ten Thousand Yrs.
Every 100 Thousand Yrs.
Every Million Yrs.
Every 10 Million Yrs.
"ANNUAL EVENT" ~20 kilotons
TUNGUSKA
"1000 YEAR EVENT" ~50 megatons
GLOBAL CATASTROPHE THRESHOLD
1/100
1
100
10,000
1 million
MEGATONS TNT EQUIVALENT ENERGY


CHANCE PER YEAR
10-2
10-4
10-6
10-8
10^10
WORLD POPULATION
10^8
10^6
10^4
10^2
EXPECTED FATALITIES IN EVENT
LOWER LIMIT
TOON (1991)
SAN JUAN CONSENSUS
CERTAIN GLOBAL CATASTROPHE
TUNGUSKA
KT IMPACT
MEGATONS
0.1
10
10^3
10^5
10^7
10^9
20 m
200 m
2 km
20 km
DIAMETER OF OBJECT

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AIAA Position Paper
The NEO Survey Workgroup Report
The Spaceguard Survey Report
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Presentation Materials

5.1 Introduction

It is feasible to conduct a survey for NEOs that will identify a large fraction of the asteroids or comets that are potentially hazardous to Earth (defined, for our purposes, as those that can come within about 0.05 AU, or about 20 times the distance to the Moon). Our objective in this chapter is to describe survey strategies that will yield a high percentage of potentially hazardous ECAs and short-period comets larger than 1 km diameter, and will provide adequate warning for some fraction of hazardous long period comets. This same approach will also yield many discoveries of smaller bodies, some of which are potential hazards on a local or regional basis.

A comprehensive survey requires monitoring a large volume of space to discover asteroids and comets whose orbits can bring them close to the Earth. Such bodies can be distinguished from main-belt asteroids by their differing motions in the sky and, in the case of comets, by visible traces of activity. To ensure reasonable levels of completeness, the volume within which we can find a 1-km or larger asteroid should extend as far as the inner edge of the main asteroid belt. Such a search could be carried out in the visible or infrared part of the spectrum, using telescopes on the Earth or in space. The analysis in this Chapter is directed toward detection of the visible sunlight reflected from these NEOs, with no distinction made between telescopes on the ground or in orbit. However, since the least expensive option -- ground-based astronomical telescopes with CCD detectors -- is capable of meeting our survey requirements, we recommend this simple and cost-effective approach.

In this chapter we define a search strategy and use computer modeling to explore its quantitative implications. In Chapter 6 we will describe the follow-up observations required to refine the orbits of newly discovered objects, and in Chapter 7 we will present a proposed plan for an international network of survey telescopes to carry out this program.

limited funding resources has resulted in a current program to find and track NEOs that is quite fragmentary. Generally it has been possible, in recent years, for discoveries made by one team to be followed up by other observers, but this has not always been the case, allowing some newly-discovered NEOs to be lost. For the program planned here this must not be allowed to occur, emphasizing the need for an international effort with close cooperation and priorities to be set by a central organization. The present level of our knowledge of NEO's has only been possible because of the services of the staff of the Central Bureau for Astronomical Telegrams and the Minor Planet Center (Cambridge, Massachussetts) who coordinate the analysis of observations of NEO's and make every effort to ensure that sufficient coverage occurs. A continuation of such a service on a larger scale will be necessary if the proposed program is to be brought to fruition.

There have in the past been some efforts made at formally organizing a search program on an international scale, quite apart from the informal links and communications made possible by personal contacts. The most prominent of these organizations has been INAS, the International Near-Earth Asteroid Survey, coordinated by E.F. Helin (Helin and Dunbar, 1984, 1990). INAS has resulted in increased cooperation between observatories in various countries, and hence an increase in the discovery rates. Apart from the U.S., scientists from the following countries have been involved in INAS: France, Italy, Denmark, Sweden, Bulgaria, Czechoslovakia, Yugoslavia, Germany, China, Japan, Russia, Ukraine, United Kingdom, Canada, Australia, and New Zealand.

The major thrust of INAS has been to coordinate the efforts of the large wide-field photographic instruments with regard to temporal and sky coverage. An immediate expansion of this effort can increase the current discovery rate, thus providing valuable information on the true statistical nature of the NEO population and associated impact hazards before the full network of survey telescopes becomes operational. Such a program will also serve as a training ground for new personnel and provide valuable experience with improved international communication and coordination.

A Spacewatch-type telescope is currently under development in India with the joint support of the U.S. Smithsonian Institution and the Government of India. Another international effort is being proposed by the Institute for Theoretical Astronomy in St. Petersberg, Russia, under the direction of A.G. Sokolsky. This group organized an international conference The Asteroid Hazard in October 1991, which endorsed the idea that NEOs "represent a potential hazard for all human civilization and create a real threat of regional catastrophes"

and noted "the necessity of coordinated international efforts on the problem of the asteroid hazard." This group has asked the Russian Academy of Science to support the formation of an International Institute on the Problem of the Asteroid Hazard under the of the International Center for Scientific Culture -- World Laboratory, and they propose to coordinate asteroid search and follow-up observations in central and eastern Europe.

8.3 Funding Arrangements

If this international survey program is to succeed, it must be arranged on an inter-governmental level. To ensure stability of operations, the NEO survey program needs to be run by international agreement, with reliable funding committed for the full duration of the program by each nation involved.

There are good reasons for the funding to be expected to be derived from all nations directly involved in the program. First, most countries usually want to provide for their own defense rather than to rely upon another or others to do this for them, so we may anticipate that nations in the world-wide community will wish to each play their own part in defending the planet. Second, although this program is large compared with present NEO search efforts, in fact it would be of quite a small overall budget. Thus it is possible for nations to make a significant contribution with little expense whereas it would not be possible for them to buy into a large space project, or even the construction of a ground-based 10-meter-class astronomical telescope. For example, there is a small group in Uruguay who study dynamical aspects of NEO's, and they could provide an essential service to the program; or the telescopes available for follow-up work in New Zealand or Romania could be utilized, and thus those nations gain prestige on the international scene at little expense. Involvement in space programs (which this program is, in essence) is generally viewed favorably by the populace of most countries. Third, this program may be a significant technology driver, so that money spent on the investigation and development of new technologies can be viewed as an investment rather than an expenditure.

With the encouragement of the United States as prime mover, the

funding for national sectors of the overall international search program should be attainable locally. For example, Australia and the United Kingdom, through their joint observatory in Australia, could immediately boost the current discovery rate to about 100 per year using existing equipment and technology given supplementary funding from those countries of the order of $0.25 million per year, although we would anticipate that this effort would be superseded by the introduction of CCD detectors within five years. Photographic searches currently being carried out in the United States might require a similar boost in funds, with a concomitant boost in discovery rate resulting, and the Spacewatch effort could also be significantly expanded by approval for the upgrade to 1.8-m aperture and funding to run the camera on more than eighteen nights per month.

8.4 International Sanction

The astronomical program outlined in this report already has the support of various international bodies. There is a burgeoning awareness in the astronomical community that the NEO impact hazard is a topic that requires attention for reasons other than altruistic scientific pursuit. At the 1991 General Assembly of the International Astronomical Union held August 1 in Buenos Aires, Argentina, the following resolution was passed:

> The XXIst General Assembly of the International Astronomical Union,
>
> Considering that various studies have shown that the Earth is subject to occasional impacts by minor bodies in the solar system, sometimes with catastrophic results, and
>
> Noting that there is well-founded evidence that only a very small fraction of NEO's (natural Near-Earth Objects: minor planets, comets and fragments thereof) has actually been discovered and have well-determined orbits,
>
> Affirms the importance of expanding and sustaining scientific programmes for the discovery, continued surveillance and in-depth physical and theoretical study of potentially hazardous objects, and

Resolves to establish an ad hoc Joint Working Group on NEOs, with the participation of Commissions 4, 7, 9, 15, 16, 20, 21 and 22, to:

1. Assess and quantify the potential threat, in close interaction with other specialists in these fields
2. Stimulate the pooling of all appropriate resources in support of relevant national and international programmes;
3. Act as an international focal point and contribute to the scientific evaluation; and
4. Report back to the XXIInd General Assembly of the IAU in 1994 for possible further action.

The Working Group, to be convened by A. Carusi of Italy, comprises the following scientists:

A. Bazilevski (USSR)
A. Carusi (Italy)
B. Gustafson (Sweden)
A. Harris (USA)
Y. Kozai (Japan)
G. Lelievre (France)
A. Levasseur-Regourd (France)
B. Marsden (USA)
D. Morrison (USA)
A. Milani (Italy)
K. Seidelman (USA)
G. Shoemaker (USA)
A. Sokolsky (USSR)
D. Steel (Australia/UK)
J. Stohl (Czechoslovakia)
Tong Fu (China)

This Working Group was selected not only on the basis of the geographical spread of persons active in the general area, but also in terms of expertise in distinct areas of the necessary program (e.g. celestial mechanics, generation of ephemerides, physical nature of NEO's, dynamics of same, relationship to smaller meteoroids and interplanetary dust). Five of these 16 individuals are also members of the NASA International NEO Detection workshop, ensuring appropriate continuity of effort.

Next Chapter

5.2 Population Statistics of NEOs

To develop a quantitative survey strategy, we begin with the model for the Earth-approaching asteroids and comets that was developed in Chapter 3. Although only a small fraction of these near-Earth asteroids and comets are now known, we have sufficient information to characterize the population for purposes of search simulation.

5.2.1 Asteroids

We have used the set of 128 known ECAs (Table 3.1) in carrying out search simulations. Our objectives are defined in terms of discovery of these ECAs. This survey will also discover a large number of closely related Amor asteroids whose orbits will become Earth-crossing some ten or hundreds of millions of years i the future. The survey is also capable of discovering small main-belt asteroids, at a rate about a thousand times greater than that of the ECAs.

The known ECA population is biased by observational selection (which tends to favor objects with orbits that bring them often into near-Earth space) and by the reflectivities of the bodies' surfaces (which favors the detection of bright objects over dark ones). Muinonen and others (1991) computed encounter velocities and collision probabilities of individual asteroids to correct for known sources of bias. The diameter distribution was approximated by a power law, as described in Chapter 3. For our model simulation, there are about 2,100 ECAs larger than 1 km diameter, 9,200 larger than 0.5 km, and 320,000 larger than 0.1 km. Of those larger than 0.5 km in diameter, about 2 percent are Atens, 75 percent are Apollos, and 23 percent are Earth-crossing Amors. Although the ECA population is uncertain by as much as a factor of two, particularly at the smallest diameters, the results of simulated surveys and the indications they provide about observing strategy should be qualitatively correct.

5.2.2 Comets

Since the orbits of short-period comets (those with periods less than 20 years) are rather similar to the ECAs, no special strategy needs be devised to discover these comets. Indeed, the activity of most short-period comets makes them brighter and thus will enhance their discovery relative to ECAs of the same diameter. In what follows, the modeling of the discovery of ECAs should be taken to include that of short period comets.

The intermediate and long-period comets are quite different from short-period comets. For purposes of this report, we use the term ECC (Earth-crossing comet) for all comets with period greater than 20 years and perihelion distances less than 1.017 AU. Because the majority of the ECCs discovered will make just one passage through the inner solar system during a survey of 15- to 25-yr duration, they do not provide the repeated opportunities for discovery that exist for the ECAs. The best we can do is to identify incoming ECCs in time to give the longest possible warning time of their approach. For our simulations,we have used a sample of 158 ECCs observed during the last 100 years. We assume that the observations represents an unbiased sample of the true ECC population. According to this model, there are about 180 ECCs/year larger than 1 km diameter that pass within the orbit of the Earth.

In simulating the ECCs, we have also taken into the account their activity (formation of an atmosphere), which causes them to brighten much more rapidly as they approach the Sun than would be expected from their size alone. The presence of an atmosphere enhances the detectability of comets, but the effect is not large until the comet comes inside the orbit of Jupiter, at which point we typically have only about one year warning.

5.3 Spatial and Sky-Plane Distributions of NEOs

Figure 5-1 shows the locations of the known ECAs on 23 September 1991 as seen from north of the plane of the solar system. About 10 percent are inside the Earth's orbit, and about 25 percent inside Mars'; these percentages should not vary much with time. Most of the ECAs are rather distant, the median geocentric distance being about 2.2 AU (where 1 AU is 150 million kilometers or about 375 times the distance to the Moon). Assuming practical observational limits of magnitude V = 22 and solar elongations greater than 75 deg (to be discussed in greater detail below), about one third of the known ECAs are observable from the Earth at any time.

The model population described above has been used to estimate the apparent or sky-plane distribution of ECAs (Muinonen and others 1991). From Figure 5-2, one expects a prevalence of small (faint) ECAs in the opposition and conjunction directions (that is, toward the Sun and away from the Sun). We also expect a concentration toward the ecliptic, the central plane of the solar system. These expectations are confirmed in Figure 5-3, which shows instantaneous number-density contours of ECAs larger than 0.5 km diameter for limiting magnitudes V = 18, 20, and 22 (note that larger magnitudes refer to fainter objects). Near opposition, and ignoring detection losses other than trailing produced by the apparent motion of the object, about 300 square degrees must be searched to V = 18 to be almost certain of detecting an ECA. To detect one ECA at V = 20 we must search 50 square degrees, and 15 square degrees at V = 22.

5.4 Modeling Whole-Sky Surveys

To estimate the likely outcome of an ECA search program and to devise a sound observing strategy, Bowell and others (1991) used the model ECA population described above to simulate the results of 10-yr surveys. Their results have since been expanded to include LPCs in the simulations described in this report. Factors investigated are: limiting search magnitude; search area and location; observing frequency; and survey length. The simulations not only predict the percentage completeness of NEO discovery as a function of diameter, but they also impose requirements on instrumentation and software, suggest some of the necessary capabilities of a global network of observing stations, and give pointers on follow-up and orbit-determination strategy.

To model the expected rate of discovery of ECAs and ECCs, and to understand how a survey for ECAs can be optimized, we have allowed for the effects of detection losses -- that is, of factors that cause some objects to be missed or reduce the probability of their detection. These losses include trailing (as noted above), confusion with main-belt asteroids, confusion with stars and galaxies, and so-called "picket-fence" losses in which an asteroid's rapid motion across the sky causes it to be missed as a consequence of the fact that only a small potion of the sky is directly observed at any one time.

No survey will cover the entire sky because of interference from the Sun and Moon and other practical considerations. But as a reference, let us calculate the percentage completeness of NEOs that would be discovered in a hypothetical whole-sky survey as function of diameter, limiting magnitude, and survey duration. Figure 5-4 illustrates the results of ECA-survey simulations in which detection losses are allowed for and in which the whole sky is searched once each month. At a limiting magnitude of V = 18, comparable to the limit of the 0.46-m Palomar Schmidt telescope currently used for several photographic surveys, even whole-sky surveys extending as long as 25 years would not yield a large fraction of the largest ECAs. The problem is that the volume of space being searched is so small that many of the ECAs of interest simply do not pass through the region being surveyed in a 25 year span. At V = 20, which is somewhat inferior to the current performance of the 0.9-m Spacewatch Telescope, about half the ECAs larger than 1 km diameter are accessible in 15 years. To achieve greater completeness, and therefore greater levels of risk reduction, we must utilize larger telescopes with fainter limiting magnitudes, as will be described in Chapter 7.

At fainter magnitudes, much greater completeness is attainable, and discovery is characterized by a rapid initial detection rate followed after some years by a much slower approach to completeness. To survey, for example, 90 percent of ECAs larger than 1 km, a large area of the sky must be searched each month for a number of years to a magnitude limit of V = 22 or deeper. Because of the rapid decline in the rate of discovery of large ECAs, surveys lasting many decades or even longer are mainly valuable for providing increasing discovery completeness of smaller ECAs (less than 1 km diameter) and continued monitoring of ECCs.

The ECCs spend almost all of their time in the outer solar system, and they can approach the inner solar system from any direction in space. Those with Earth-crossing orbits (that is, with perihelia within 1 AU of the Sun), take about 16 months to travel from the distance of Saturn (9.5 AU from the Sun) to that of Jupiter (5.2 AU) and a little more than an additional year to reach perihelion. At any time, it is estimated that at least one thousand ECCs are brighter than V = 22 magnitude.

Modeling searches of the whole sky once a month for ECCs to magnitude limits of V =22 and 24 reveals the shortness of the warning time even for faint limiting magnitudes. For V=22, we would discover 93 percent of ECCs larger than 1-km diameter with three months warning time, but only 16 percent with one year warning time. For V=24, the corresponding numbers would be 97 and 72 percent. For ECCs larger than 0.5 km, the discovery completeness would be 85 and 6 percent for V=22, and 95 percent and 24 percent for V=24.

D > (km)	Warning time (yr)	% LPCs discovered V = 22	V = 24
1.0	0.25	91	97
	0.5	58	88
	1.0	10	43
5.0	0.25	96	99
	0.5	90	92
	1.0	67	83
	2.0	8	25
10.0	0.5	92	95
	1.0	76	88
	3.0	7	28

From these numbers, it is clear that a high discovery percentage can only be achieved for warning times on the order of several months, even for a very deep limiting magnitude of V = 24. This result confirms our intuition that it is much more difficult to provide long lead times for ECCs than for ECAs.

5.5 Search Area and Location

The reference case described in Section 5.4 refers to a hypothetical full-sky survey. Now we turn to the real world. What area of sky is it necessary to search, and in what locations, in order to discover a sample of ECAs and ECCs that is reasonably complete to an acceptable diameter threshold?

First we consider searching the maximum possible amount of dark sky. It is practicable to observe a region extending as much as +/-120 deg celestial longitude from opposition and +/-90 deg celestial latitude. In sumulation such a survey, we include all the detection losses previously mentioned. Table 5-1 shows the calculated discovery completeness for a 25-year monthly dark-sky survey for ECAs. For V=22 and all ECAs larger than 1-km diameter (potentially hazardous ECAs will be treated in more detail in Section 5.7.3),kthe discovery completeness would be very high: 95 percent. For V=24, we would virtually achieve total completeness.

Table 5-2 shows the result of a perpetual monthly dard-sky survey for ECCs. Now, for V=22 and D>1 km, the completeness with a short warning time of thre months is 77 percent. For V-24, we wouldachieve 92 percent discovery completeness. In contrast to ECAs there is appreciable degradation of discovery com;leteness for ECCs arising from lack of observation at small solar elongations and low galactic latitudes.

Figure 5-3 indicates that a search centered on opposition (opposite the direction toward the Sun) is optimum. Surveys have been simulated that cover various areas of the sky and in which realistic detection losses have been included. In particular, sumulations of 25-yr surveys to V = 22 for ECAs larger than 0.5 km diameter show that to minimize the area coverage needed to achieve a given discovery completeness, it is clearly advantageous to search regions spanning a broader range of celestial latitude than celestial longtude. The same strategy holds for other magnitude and diameter thresholds. For plausible search areas (in the range 5,000 to 10,000 square degrees per month), one may anticipate about two-thirds discovery completeness at V = 22. However, coverage in both longitude and latitude must not be too small or ECAs will pass through the search region undetected from one month to the next.

Atens pose a special problem because some of them make very infrequent appearances that may occur far from opposition in celestial longitude. It can be expected that only about 40 percent of the Atens sought would be discovered in a nominal 25-yr, 6,000-square degree per month survey. The discovery rate could be increased to nearly 60 percent by biasing the search away from opposition, but at a sacrifice in the overall ECA discovery rate. It should be recalled that only eleven Atens are known, so the bias-corrected estimate of their true number may be substantially in error.

5.6 Discovery Completeness

In what follows, it will be useful to consider a so-called standard survey region of 6,000 square degrees, centered on opposition and extending +/-30 deg in celestial longitude and +/-60 deg in celestial latitude.

5.6.1 Asteroids

To increase discovery completeness for a given search area and minimum ECA diameter, either the survey must be lengthened, the sky must be searched more frequently, the limiting magnitude must be increased, or detection losses must be reduced.

As noted above, rapid decline in discovery rate of ECAs at faint magnitudes makes increasing the duration of the survey an ineffective strategy. For reference, the whole-sky survey to V = 22 and for diameter greater than 0.5 km could yield 71 percent completeness after 10 years. Even after 20 years, completeness would rise only to 81 percent (Figure 5-4).

Scanning a given region of the sky twice a month is likewise not very effective. For the standard 6,000 square degree survey region, to V = 22 and 0.5-km diameter threshold, the completeness after 25 yr would rise from 66 percent to 69 percent. However, scanning 12,000 square degrees once per month could lead to 72 percent completeness.

Figures 5-4 and 5-5 attest to the high value of mounting very deep surveys (that is, to very faint magnitude limits) for ECAs, the key factor being the greatly increased volume of space in which ECAs of given diameter can be detected. Figure 5-5 shows discovery completeness as functions of limiting magnitude V and diameter threshold for the standard survey region. At V= 20 and for diameter greater than 0.5 km, one can expect the standard 25-yr survey to be only 27 percent complete, whereas at V = 22 completeness rises to 66 percent. If the diameter threshold is 1 km, completeness should increase to 54 percent and 88 percent, respectively. Table 5-3 summarizes the results form the standard 25-year survey for ECAs, and shows that a signivicant fraction of small ECAs could be discovered.

Examination of the orbits of ECAs not discovered during simulated surveys shows, not unexpectedly, that most of these bodies' orbits have large semimajor axes, high eccentricities, and/or high inclinations such that either their dwell times in near-Earth space are brief and infrequent or they never come close to Earth in their present orbits. Of course, the latter class of ECAs poses no current hazard. This result of the simulations thus confirms our intuition: the survey preferentially discovers objects that come close to the Earth and therefore favors our overall objective of reducing the hazard of impacts on our planet.

5.6.2 Comets

No survey can aspire to completeness in the discovery of ECCs, since new comets are constantly entering the inner solar system. Results for ECCs in a 6,000-square-degree per month survey to V = 22 and 24 are given in Table 5-4. As before, calculations are for a perpetual survey.

D > (km)	Warning time (yr)	% LPCs discovered V = 22
1.0	0.25	29
	0.5	15
	1.0	3
5.0	0.25	48
	0.5	37
	1.0	17
	2.0	3
10.0	0.5	44
	1.0	25
	2.0	7
	3.0	4

The warning time used in these calculations is actually the time from discovery to first Earth crossing. But it is equally likely that the ECC, if it is on a collision course, will strike Earth on the outbound part of its orbit, increasing the warning by a few weeks.

The overall level of completeness, without regard to warning time, is 37 percent at 1 km, 54 percent at 5 km, and 57 percent at 10 km diameter. Clearly, a survey designed for ECAs produces inferior results for ECCs, although the rate of discovery of these comets will be much greater than that achieved by current surveys, which rely upon relatively small telescopes and visual sky-sweeping by amateur astronomers and miss the great majority of the smaller long-period comets.

5.7 Simulated Survey Scenarios

The simulations described above can be used to infer what the nature of the observing activity during each monthly run of a major survey might be. The standard survey region of 6,000 square degrees per month can be studied for this purpose.

5.7.1 Discovery of Very Small ECAs

Thus far, there has been no consideration of ECA discoveries smaller than specified diameter thresholds, though it is obvious that many smaller bodies will be detected (see Tables 5-1 and 5-3). To estimate how many, 25-yr surveys of the 320,000-member model population of ECAs larger than 0.1 km were simulated. From Fig. 5-6, which shows size-frequency distributions of ECA discoveries for various magnitude limits V, that many more ECAs smaller than the nominal diameter thresholds (0.5 to 1 km) would be discovered than those being targeted. Thus, for a survey to V = 22, one would expect about 80,000 ECA discoveries, of which 60 percent are smaller than 0.1 km, 92 percent are smaller than 0.5 km, and 98 percent are smaller than 1 km diameter. In other words, for every object greater than 1 km diameter discovered in the standard survey, 50 more will be found that are smaller than 1 km.

5.7.2 Monthly Discovery Rate

What would be the discovery rate per month, assuming that the standard survey region of 6000 square degrees were scanned? Figure 5-7 indicates that, to V = 22, one can expect more than 500 ECA discoveries of all diameters during the first month. This high initial monthly discovery rate is expected to tail off by a factor of about two over the course of a 25-yr survey. The larger ECAs are preferentially discovered early, so that while about 5 percent of the ECAs discovered will be larger than 1 km diameter at the beginning of the survey, only 0.1 percent of the discoveries will be larger than 1 km diameter after 25 years. We estimate that ECCs larger than 0.5 km diameter will be discovered at a steady rate of about 15 per month.

5.7.3 Potentially Hazardous NEOs

Not all NEOs pose a threat to Earth. Many of them are in orbits that cannot, at present, bring them within a distance that we should be concerned about. The potential threat of an ECA or ECC can be gauged from the minimum distance of its orbit from that of the Earth (it can be assumed that, at some time or another, an ECA will be located at the minimum distance). For ECAs that are not predicted to make very close planetary encounters (and thus will not have their orbits changed abruptly), we estimate that, over a timespan of a few hundred years, minimum Earth-encounter distances will not change by more than ten lunar distances (0.02-0.03 AU) in response to planetary perturbations. Thus, we can be sure that ECAs whose minimum inner-planet encounter distances are larger than, say, 20 lunar distances, will not pose a threat to Earth in the coming centuries. For statistical purposes, we assume the same to be true of ECCs. Objects with smaller encounter distances we regard as potentially hazardous.

Because ECAs are preferentially observable when close to Earth, the completeness level for potentially hazardous ECAs is greater than that of the population as a whole. For the standard survey (Table 5-1), the discovery completeness of potentially hazardous ECAs is 91 percent for bodies larger than 1 km diameter (compared to 87 percent for the entire ECA population) and 73 percent for ECAs larger than 0.5 km diameter (compared to 66 percent). For LPCs, however, the discovery completeness is the same as that of the total population (Tables 5-2 and 5-4).

As in Chapter 3, we suppose that 75 percent of the NEO hazard arises from ECAs and 25 percent from ECCs. If we specify a 3-month warning time for ECCs, the percentages of potentially hazardous objects larger than a given diameter discovered during a standard 25-yr survey are as follows: 76 percent at 1 km diameter, 79 percent at 5 km, and 81 percent at 10 km or larger. At the larger sizes, the missed objects are almost all comets, and they will be detected, but not with a full year warning time.

Chapter 5: Search Strategy
5.1 | 5.2 | 5.3 | 5.4 | 5.5 | 5.6 | 5.7 | 5.8

5.8 Practical Considerations in Search Strategy

It is inconceivable that a fully fledged network of completely equipped observing stations will start operation simultaneously and at full efficiency. More likely, current photographic and CCD searches will be intensified in parallel with the development of new survey telescopes. There exists, therefor, an important opportunity to refine models of the NEO population and to test observing strategies. In particular, care should be taken to preserve the pointing histories of any systematic searches for NEOs so more reliable bias correction can be carried out as the known sample grows. When a full-up survey is in progress, it will be possible to refine the population model further. For example, if it is determined that Atens are more numerous than presently thought, an improved survey strategy could be designed to enhance their discovery. Additional physical observations of newly discovered ECAs will also permit us to improve the model and thus develop better observing strategies.

We have shown that potentially hazardous ECAs can be discovered at a sufficient rate that most of the larger members of the ECA population can be discovered and assessed within 25 years. By prolonging the survey, the inventory of smaller ECAs can be brought to greater completeness. Indeed, we estimate that, using current technology to continue the standard survey beyond 25 years, we would stand a better-than-even chance, within a few hundred years, of discovering and identifying the ECA that might cause the next Tunguska-like event. In anticipation that huge strides in technological development would reduce this interval considerably, we can be almost certain that the such an impactor could be identified by means of a prolonged telescopic search.

Since ECCs enter the inner solar system at a near-constant rate, many of them for the first time, their potential for hazard to Earth goes on forever. Thus, any survey of finite duration will be destined to ignore about 25 percent of the potential hazard posed to our planet. Only by continually monitoring the flux of ECCs into Earth's neighborhood can we hope to achieve near-complete assessment of the NEO hazard.

Next Chapter

Chapter 7: Proposed Search Program
7.1 | 7.2 | 7.3 | 7.4 |7.5 | 7.6 | 7.7

7.1 Introduction

In this chapter, we assess the instrumental requirements (telescopes, mosaics of CCD chips, computers, etc.) imposed by the observing strategy and follow-up research outlined in Chapters 5 and 6, and we comment on observational techniques and observing network operation. In order to cover the requisite volume of search space, the survey must achieve a stellar magnitude limit of at least V = 22, dictating telescopes of 2- to 3-m aperture equipped with CCD detectors. The most efficient use of CCD detectors is achieved if the pixel size is matched to the apparent stellar image size of about 1 arcsec, thus defining the effective focal length for the telescopes at about 5 m. The area of sky to be searched is about 6,000 square degrees per month, centered on opposition, and extending to +/- 30 deg in celestial longitude and +/- 60 deg celestial latitude. These considerations lead us to a requirement for multiple telescopes with moderately wide fields of view (at least 2 degrees) and mosaics of large-format CCD detectors. We develop these ideas in this chapter to derive a proposed search program. This program is not unique (that is, an equivalent result could be obtained with other appropriate choices of telescope optics, focal-plane detectors, and locations), but it is representative of the type of international network required to carry out our proposed survey.

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7.2 Lessons From the Spacewatch Program

The Spacewatch Telescope, operated at the University of Arizona (see Chapters 3 and 4), is the first telescope and digital detector system devised to carry out a semi-automated search for NEOs. As such, the lessons learned from its development and operation are invaluable when considering a future generation of scanning instruments. The Spacewatch system comprises a single 2048x2048-pixel CCD chip at the f/5 Newtonian focus of an equatorially mounted 0.91-m telescope. Each pixel covers 1.2 x 1.2 arcsec on the sky. With the telescope drive turned off, the camera scans the sky at the sidereal rate, and achieves detection of celestial bodies to a limiting magnitude V = 20.5.

One of the important demonstrations provided by the Spacewatch Telescope team is that image-recognition algorithms such as their Moving Object Detection Program (MODP) are successful in making near-real-time discoveries of moving objects (asteroids and comets). False detections are almost eliminated by comparing images from three scans obtained one after the other. At present, the Spacewatch system makes detections by virtue of the signal present in individual pixels. With the incorporation of higher-speed computers, near-real time comparison of individual pixels to measure actual image profiles would lead to a great reduction in the most frequent sources of noise, cosmic ray hits and spurious electrical noise events.

In light of the successful performance of Spacewatch, we have rejected a photographic survey. Even though sufficiently deep exposures and rapid areal coverage could be attained to fulfill the survey requirements using a small number of meter-class Schmidt telescopes (similar to the Oschin and U.K. Schmidts), there is no feasible way, either by visual inspection or digitization of the films, to identify and measure the images in step with the search. A photographic survey would fail for lack of adequate data reduction and follow-up. Future developments in electronics and data processing will further enhance the advantages of digital searches over the older analog methods using photography.

7.3 Detector and Telescope Systems

The largest CCD chips readily available today contain 2048x2048 pixels, each about 25 micrometers on a side. Thus, the chips are about 5x5 cm in size. Quantum efficiencies have attained a peak near 80 percent, and useful sensitivity is achievable from the near-ultraviolet to the near-infrared. To reach a limiting stellar magnitude of V = 22, we require the use of these CCDs at the focal plane of a telescope with an aperture of 2 m or larger, operated during the half of the month when no bright moonlight is present in the sky (from last quarter to first quarter phase).

In the coming decade, we envisage a trend toward smaller and more numerous CCD pixels covering the same maximum chip area as at present. No great increase in spectral sensitivity can be expected. At the telescope, the pixel scale must be matched to the image scale (the apparent angular size of a stellar image) in good or adequate atmospheric (seeing) conditions. In what follows, we assume a pixel scale of 1 arcsec/pixel (25-micrometer/arcsec, or 40 arcsec/mm), which implies a telescope of 5.2-m focal length. For a telescope of 2 m aperture, the focal ratio is f/2.6; for a 2.5-m, f/2.1; and for a 3-m, f/1.7.

A single 2048x2048 CCD chip simultaneously detects the signals from more than 4 million individual pixels. This is a very powerful data-gathering device, but it still falls short of the requirements for wide-field scanning imposed by the proposed NEO survey. At the prime focus of a telescope of 5.2 m focal length, such a CCD covers a field of view on the sky about one half degree on a side. However, we wish to scan an area at least 2 degrees across. Therefore, we require that several CCD chips be mounted together (mosaicked) in the focal plane. The mosaicking of CCD chips is being vigorously pursued today by astronomers. At Princeton University, for example, a focal plane with 32 CCDs is under development.

Studies and planning are underway at the University of Arizona for a modern 1.8-m Spacewatch telescope. The new telescope will be an excellent instrument to test and develop some of the necessary instrumental and strategic considerations outlined in this report. From the Spacewatch design considerations, it is safe to assume that 2- to 3-m-class telescopes can be built having focal lengths near 5 m and usable fields of view between 2 and 3 deg. Refractive-optics field correction is probably required, and it appears advantageous to locate CCD mosaics at the prime focus of such instruments. Here, we indicate telescope functional requirements but do not exactly specify the size or design of the proposed survey telescopes.

7.4 Magnitude Limit and Observing Time

Exceptionally fine astronomical sites have more than 1,000 hr/yr of clear, moonless observing conditions, during most of which good to adequate seeing prevails. More typically, 700 hr/yr of observing time is usable. We assume that a region of 6,000 square degrees is to be searched each month and that initial NEO detection is made by two or three scans on the first night. Parallactic information is derived by four scans on a subsequent night, and an orbit is calculated from observations on a third night. Thus, nine or more scans of the search region are needed each month. In a given month, follow-up will be attempted for some of the NEOs that have moved out of the search region (mainly to the west). As a working value, we assume that 40 hr/month/telescope are available for searching.

The limiting (faintest) stellar magnitude that can be observed by a telescope can be determined as a function of the ratio of the source brightness to that of the sky, the number of pixels occupied by a star image, the pixel area, the light-collecting area of the telescope, and the effective integration time (Rabinowitz 1991). For certain detection, the source brightness must be at least six times that of the sky noise. We have normalized to the performance of the Spacewatch Telescope, which achieves a stellar limit of V = 20.5 using an unfiltered 165-sec scan at sidereal rate, and we have allowed for an improvement over the performance of that system arising from improved detector quantum efficiency and improved image-recognition algorithms. We find for the survey telescopes that a single CCD should be able to achieve the survey requirement of V = 22 with the following combinations of telescope aperture and scan speed:

Primary Diameter (m)	Exposure Time (s)	Scan Rate (x sidereal)
2.0	21	6
2.5	14	10
3.0	10	14

7.5 Number of CCD Chips and Telescopes Required

A single 2048x2048-pixel CCD chip, having an image scale of 1 arcsec/pixel, can scan at 0.14 square degrees per minute at the sidereal rate. If 40 hr/month/telescope can be allotted to searching for NEOs over 6,000 square degrees to a limiting stellar magnitude of V = 22, and ten scans per sky region are required for detection and rough orbital characterization of an NEO, then telescopes of the apertures considered above have the following performance capabilities:

Primary Diameter (m)	Exposure Time (s)	Scan Rate (x sidereal)
2.0	260	28
2.5	420	18
3.0	500	13

In computing values for the total number of CCD chips required in the worldwide network of telescopes we assume that no two CCD chips together scan the same region of the sky. These are minimum requirements for the telescopes; in practice more scans may be needed for reliable automatic detection, and probably there will be some overlap of coverage between telescopes.

Searching to +/- 60 deg celestial latitude implies sky coverage, over the course of a year, at almost all declinations. Thus telescopes must be located in both hemispheres. Usable fields of view of between 2 and 3 deg probably limit the number of CCD chips in a telescope's focal plane to about ten at the scales we have been considering. However, real-time image processing is simplified if each chip independently samples the sky. Most likely, four CCDs chips/telescope can be accommodated in a linear array in the focal plane. Thus, it appears that seven 2-m telescopes, five 2.5-m telescopes, or four 3-m telescopes suffice to fulfill the search, follow-up, and physical observations requirements of the idealized 6,000-square degree survey. Most likely, there would remain extra observational capability to enhance the detection rates of Atens and ECCs by scanning a few times per month outside the standard region. We note that each telescope must be equipped with a minimum of four 2048x2048 CCD chips or their equivalent in light-collecting ability. If space remains in the focal plane, additional filtered CCD chips could be inserted to undertake colorimetry, which would give a first-order compositional characterization of some of the NEOs discovered while scanning.

If a single-point failure due to weather or other adverse factors is not to hamper effective operation of the survey network, we conclude that three telescopes are required in each hemisphere. With fewer telescopes, orbital, and perhaps parallactic, information on NEOs would be sacrificed. The desirability of searching near the celestial poles calls for at least one telescope at moderate latitude in each hemisphere. In summary, we propose a network of six 2-m or larger telescopes distributed in longitude and at various latitudes between, say, 20 deg and 40 deg north and south of the equator.

7.6 Scanning Regime

At high declinations, scanning along small circles of declination results in curvature in the plane of the CCD chip, so star images do not trail along a single row of pixels. The problem can be avoided by scanning along a great circle. A good strategy would be to scan in great circles of which the ecliptic is a meridian (the pole being located on the ecliptic 90 deg from the Sun). Such scanning can be achieved using either equatorial or altazimuth telescope mounts, but is probably more easily and cheaply accomplished using an altazimuth mount. In either case, field rotation is required, as is currently routinely used at the Multiple-Mirror Telescope in Arizona and other installations.

At the proposed 1.8-m Spacewatch telescope, it is planned to make three scans of each region of the sky (as is currently done at the 0.9-m Spacewatch telescope). Each scan would cover 10 deg in 26 min, so the interval between the first and third scans is sufficiently long that objects moving as slowly as 1 arcmin/day can be detected. For the proposed NEO survey, we envisage two or three longitudinal scans per sky region, about an hour apart. Thus, at a scan rate of 10 times sidereal, each scan could cover an entire strip of the 60-deg-wide search region, with a second search strip being interposed before the first was repeated. We assume that false positive detections, being somewhat rare, will not survive scrutiny on the second night of observation, and thus will not significantly corrupt the detection database.

7.7 Computer and Communications Requirements

Near real-time detection of faint NEOs requires that prodigious amounts of data processing be accomplished at the telescope. The image processing rate scales linearly with the number of objects (NEOs, stars, galaxies, noise, etc.) recorded per second. The number of objects detected per second (the "object rate"), and therefore computer requirements of the NEO survey outlined above, can be estimated from the current performance of the Spacewatch Telescope. The computer system in use at the Spacewatch Telescope can detect up to 10,000 objects in a 165-sec exposure. Thus, its object rate is 60/sec. Scanning to V = 22 requires detection of about 30,000 objects/square degree. For an image scale of 1 arcsec/pixel, using the scanning rates tabulated above, and allowing a ten-fold increase in computing requirements to perform real-time image profile analysis, we calculate the total network computer requirement to be 2,000 to 3,000 times that at the Spacewatch Telescope. Therefore at each of six telescopes, it would be 300 to 500 times that at Spacewatch. Such a requirement, although not easy to achieve, is possible using the newest generation of parallel processors.

There are at least three levels of observational data storage that can be envisaged: (1) preservation of image-parameter or pixel data only for the moving objects detected; (2) preservation of image-parameter or pixel data for all sources detected (mostly stars); (3) storage of all pixel data. The first option is clearly undesirable, because data for slow-moving NEOs mistaken as stars would be lost. The first two options have the disadvantage that there would be no way to search the database, after the event, for sources whose brightnesses are close to the limiting magnitude and that would therefore have been discarded. The third option---the most attractive scientifically---may appear to result in serious problems of data storage and retrieval. However, we anticipate that, using technology shortly to be available, the third option is tractable.

About 500 NEOs and one hundred thousand main-belt asteroids could be detected each month--about one detection per secod of observing time. Therefore, only moderate-speed data communication is needed between observing sites and a central-processing facility. Careful observational planning will be required to ensure efficient coverage of pre-programmed scan patterns, to avoid unintentional duplication of observations, to schedule the necessary parallactic and follow-up observations, and to optimize program changes so as to maintain robustness of the survey in response to shutdowns. Successful operation of this survey system will also require the coordination and orbital computation capabilities of a modern central data clearinghouse as described in Chapter 6.

3.1 Introduction

There are two broad categories of objects with orbits that bring them close to the Earth: comets and asteroids. Asteroids and comets are distinguished by astronomers on the basis of their telescopic appearance. If the object is star-like in appearance, it is called an asteroid. If it has a visible atmosphere or tail, it is a comet. This distinction reflects in part a difference in composition; asteroids are generally rocky or metallic objects without atmospheres, whereas comets are composed in part of volatiles (like water ice) that evaporate when heated to produce a tenuous and transient atmosphere. However, a volatile-rich object will develop an atmosphere only if it is heated by the Sun, and an old comet that has lost much of its volatile inventory, or a comet that is far from the Sun, can look like an asteroid. For our purposes, the distinction between a comet and an asteroid is not very important. What matters is whether the object's orbit brings it close to the Earth -- close enough for a potential collision.

The most useful classification of NEOs is in terms of their orbits. The near-Earth asteroids are categorized as Amors, Apollos, and Atens, according to whether their orbits lie outside that the Earth, cross that of the Earth with period greater than 1 year, or cross that of the Earth with period less than 1 year (see the Glossary for precise definitions of these and other technical terms). Cometary objects are classed as short period if their periods are less than 20 years, intermediate period if their periods are between 20 and 200 years, and as long period (or "new") if their periods are greater than 200 years.

Even more relevant to this report is the definition of an Earth-crossing asteroid (ECA). These are the asteroids that have the potential to impact our planet. An ECA is defined rigorously (Shoemaker 1979, 1990) as an object moving on a trajectory that is capable of intersecting the capture cross-section of the Earth as a result of on-going long-range gravitational perturbations due to the Earth and other planets. In this case "long-range" refers to periods of tens of thousands of years. For any particular NEO, it will not be clear whether it is in fact an ECA until an accurate orbit is calculated. Thus the concept of an ECA does not apply to a newly discovered object. Ultimately, however, it is only ECAs that concern us in a program aimed at discovering potential Earth impactors. In an analogous way, we define Earth-crossing comets (ECCs) as intermediate and long period comets with orbits capable of intersecting the capture-cross-section of the Earth.

Chapter 3: The Near-Earth-Object Population
3.1 | 3.2 | 3.3 | 3.4

3.2 Asteroids and Comets in Near-Earth Space

In 1989 there were 90 known ECAs (Shoemaker 1990), while 128 ECAs were known as the time this Workshop convened in June 1991 (Appendix A). None of them is today a hazard, since none is currently on an orbit that permits collision with the Earth. But all of them are capable of evolving into Earth-impact trajectories over the next few thousand years. And, in fact, it is estimated that 20 to 40 percent of the ECAs will ultimately collide with our planet (Wetherhill, 1979; Shoemaker and others, 1990). The others will either be ejected from the inner solar system through a close encounter with the Earth or will impact or be ejected by one of the other planets before they reach the Earth.

The 128 known ECAs are comprised of 11 Atens (9 percent), 85 Apollos (66 percent), and 32 Earth-crossing Amors (25 percent). Sixty-one of these have received permanent catalog numbers, implying their orbits are well established, while preliminary orbits are in hand for 51 others. The remaining 16 are considered lost, meaning their orbits are not well enough known to predict the current locations of these bodies. Further observations of them will occur only through serendipitous rediscovery.

All ECAs brighter than absolute magnitude 13.5 are believed to have been discovered. (The absolute magnitude is defined as the apparent magnitude the object would have if it were 1 Astronomical Unit (AU), or 150 million kilometers, from both the Earth and Sun). Translated to sizes, this means all ECAs larger than 14 km have been detected for the case of low reflectivity (dark) bodies, such as C-class asteroids. The limiting diameter for a complete survey is about 7 km for more reflective objects, such as S-class asteroids. We estimate that only about 35 percent of the ECAs having absolute magnitudes brighter than 15.0 (6 and 3 km diameters, respectively, for the dark and bright cases) have been discovered. At absolute magnitude 16 (4 and 2 km), the estimated completeness is only 15 percent, while at absolute magnitude 17.7 (2 and 1 km), it is only about 7 percent. The largest ECAs are 1627 Ivar and 1580 Betulia, each with diameter of about 8 km, or slightly smaller than the object whose impact ended the Cretaceous. The smallest ECAs yet discovered are 1991 BA, an object that passed within 0.0011 AU (one-half the distance to the Moon) in January 1991, 1991 TU, which passed within 0.049 AU in October 1991; both have diameters of about 10 m.

Based on search statistics and the lunar cratering record, we estimate that the population of Earth-crossing asteroids can be approximated by several power lows, which reflect a general exponential increase in the numbers of ECAs as we go to smaller and smaller sizes. Each segment of this distribution can be described, mathematically, as follows, where N is larger than a given diameter D:

$$N = k\,D^{b}$$

where k is a constant and b is the power-law exponent. Although the general form of this size distribution is demonstrated by observations, The detailed distribution is not well known. The simulations that will be described in subsequent chapters require a model for the asteroid population, however. For our ECA population model, we estimate that changes in the power law occur at diameters of 0.25 and 2.5 km, and have adopted exponents 0f -2.6 (D<= 0.25 km), -2.0 (0.25 KM < D <= 2.5 KM), AND -4.3 (D > 2.5 KM).

Estimates for the total number of asteroids having diameters larger than values of particular interest are shown in Figure 3.1 by the solid curve. Specific population estimates at sizes of interest are indicated in the Figure, where our uncertainties are bounded by the dashed lines. For example, we estimate there are 2,100 ECAs larger than 1 km in diameter, with an uncertainty of a factor of two.

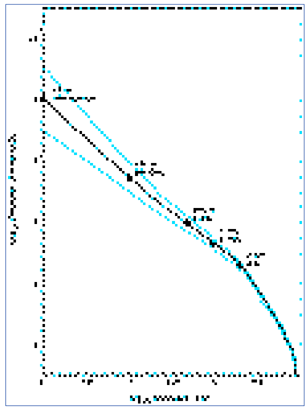

FIGURE 3.1. ***Estimated number of Earth-crossing asteroids larger than a given diameter (E. Bowell).***

Active comets can also cross the Earth's orbit with the potential for collision. From Everhart's (1967) determination of cometary orbits, it can be inferred that 10 to 20 percent of all short-period comets are Earth-crossing. Using this fraction and the frequency distribution for the number of short-period comets derived by Shoemaker and Wolfe (1982), we estimate that the population of short-period comets having Earth-crossing orbits is likely to comprise about 30 +/- 10 objects larger than 1 km diameter, 125 +/- 30 larger than 0.5 km diameter, and 3000 +/- 1000 larger than 0.1 km diameter. Comparing these numbers with those for the ECA population in Figure 3.1 shows that at any given size, short-period comets contribute only an additional 1 percent or so to the total population. This contribution is quite small compared to the estimated uncertainty in the ECA population. As stated previously, an object that displays no apparent atmosphere or tail is classified as an asteroid even if its orbital properties are similar to that of a short-period comet. Dormant or extinct short-period comet nuclei are therefore likely members of the ECA population, and such objects are implicitly included in the ECA estimates given above.

Although about 700 very-long-period or new comets are known to have passed through the inner solar system during recorded history, their total population is difficult to characterize. Only about half of these comets had Earth-crossing orbits and thus can be termed ECCs, where we define a comet to be an ECC if it has a period greater than 20 years and a perihelion less than 1.017 AU. Fernandez and Ip (1991) estimate a flux of about three ECCs brighter than absolute magnitude of10.5 per year. From work by Weissman (1991), we estimate these bodies to be between 3 and 8 km in diameter. From their orbital and size distributions, we estimate that ECCs are about five times more abundant than Earth-crossing short-period comets. Thus the combined total number of Earth-crossing comets is only about 5 -10 percent that of the ECA population. As noted previously, however, the lon-period comets contribute disproportionately to the impact flux because of their higher impact speeds, relative to those of the asteroids. Indeed, we estimate that they contribute about 25 percent of the total NEO hazard. To model the flux of ECCs that move inside the Earth's orbit, we assume a power-law distribution of 180 $D^{(-1.97)}$ per year. This flux appears to be two or three times larger than others have estimated because our model associated a larger nucleus diameter with a given apparent brightness, but the predicted number of ECCs of a given brightness should remain unaffected.

3.3 Origin and Fate of NEOs

Near-Earth objects are efficiently removed from the solar system by collisions or gravitational interactions with the terrestrial planets on time-scales of 10 -100 million years. Thus the NEO population we see today must be continually resupplied, as any remnant primordial population would have long been depleted. This process of depletion has had consequences for the geological evolution of the terrestrial planets, as evidenced by the existence of large impact basins and craters. Removal of NEOs by impacts may also have had profound consequences for biological evolution on Earth.

At the root for understanding the origin of NEOs is the need to identify their source of resupply. Cometary objects appear to be supplied from either the very distant reservoir called the Oort cloud or the somewhat closer disk called the Kuiper belt, which have preserved unprocessed (unheated) material from the time of the solar system's formation. The great age and primitive chemistry of comets make their study vital to our understanding of planetary accretion and chemistry. Galactic tidal effects and random gravitational perturbations from passing stars or molecular clouds can alter the orbits of some Oort cloud members causing them to make a close approach to the Sun. Although the comets initially have long orbital periods, they can be perturbed into short period orbits through interactions with Jupiter and the other planets.

Two sources have been hypothesized for supplying asteroidal NEOs, both with profound implications on our understanding of solar system evolution. The first hypothesis is that they are derived from main belt asteroids through the process of chaotic dynamics. It has been shown that objects orbiting in a 3:1 mean motion resonance with Jupiter (the location of one of the "Kirkwood Gaps" at 2.5 AU) exhibit chaotic increases in their orbital eccentricity allowing their orbits to cross that of the terrestrial planets. In addition to the dynamical calculations that support this hypothesis, observational evidence shows that many NEOs are compositionally similar to main-belt asteroids. In many ways, they seem to resemble the smaller main belt asteroids, and both theory and observation support the hypothesis that both groups consist primarily of fragments generated in occasional collisions between main belt asteroids.

A second proposed source for NEOs is from dormant or extinct comet nuclei. The end stages of a comet's life are poorly understood, with one scenario being that as surface volatiles are depleted an inert mantle forms which effectively seals off and insulates volatiles within the interior. Without the presence of an atmosphere or tail, such a body would have an asteroidal appearance. Observational evidence that supports this hypothesis includes several asteroidal NEOs that have orbits similar to known short period comets. At least one of these cataloged asteroids, 3200 Phaethon, is known to be associated with a meteor stream (the Geminids). Previously, meteor streams were known to be associated only with active comets. Further, the orbits of some asteroidal NEOs do not appear to follow strict gravitational dynamics, suggesting the action of some non-gravitational forces such as those associated with cometary activity.

3.4 Physical Properties of NEOs

The physical and compositional nature of asteroids and comets is inferred from telescopic observations aided by comparisons with the meteorites (Figure 3.2). Most meteorites appear to be fragments of asteroids, and in many cases it is possible to match the reflectance spectra of individual asteroids with those of meteorites measured in the laboratory. Most of this work has been done for the main belt asteroids, however, since the near-Earth asteroids are generally faint and must be observed within a rather narrow window of accessibility.

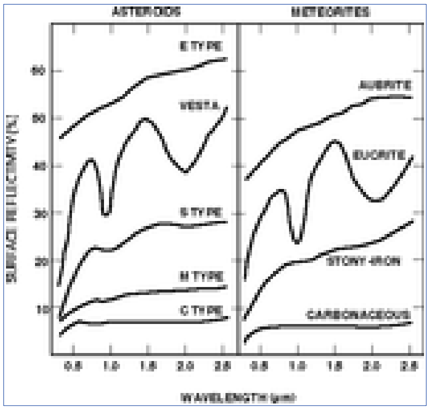

FIGURE 3.2. ***Comparison of the spectral reflectance of asteroids and meteorites (C. Chapman).***

Although most known Earth-approaching asteroids have never been observed for physical properties, and those that have been are generally only poorly observed relative to the brighter main belt asteroids, some things can be said about them. They exhibit a diversity in inferred mineralogy approaching that in the rest of the asteroid population. The majority are expected to be similar to the dark C-type asteroids in general properties (presumably moderately low-density, volatile-rich bodies, colored black due to at least several percent of opaques). There are also a large number of S types. (S's are thought to be either stony, chondrite-like objects, stony-iron objects, or a combination of both.) In addition, there are known examples of metallic bodies (probably like nickel-iron alloy meteorites) and rocky, monomineralic bodies.

These asteroids are small and often quite irregular in shape; they also tend to have rather rapid spins, but there is a great diversity in such properties. Their densities have not been measured, but are inferred to be typical of rocky material (about 2-3 g/cm^3). In only one case has an Earth-approaching object been imaged: 4769 Castalia (Figure 3.3). Remarkably, this radar image shows a highly elongated object that may be a contact-binary composed of two objects of comparable size. Although astronomers have presumed that these objects are coherent, intact bodies like large boulders, it is possible that some or many of them are aggregates, which may have little or no internal cohesion.

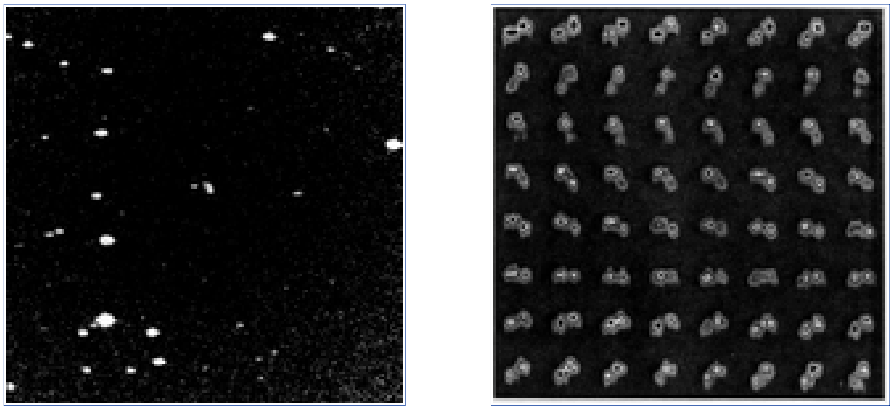

FIGURE 3.3. ***The Apollo asteroid 4769 Castalia is shown in the discovery photo at left taken on August 9, 1989 using the 0.46-m Schmidt telescope at the Palomar Observatory. Quick alerts allowed follow-up by radar observations (right) on August 22 at Arecibo, Puerto Rico. Radar images revealed the asteroid's two-lobed form and it's four hour rotation rate.*** Photographs courtesy of (left) E.F. Helin (Caltech/JPL), Planet-Crossing Asteroid Survey;(right) S. Ostro (Caltech/JPL).

Only one asteroid has been investigated by a spacecraft: in October 1991, the Jupiter bound Galileo spacecraft passed within 1,600 km of the main belt asteroid 951 Gaspra (figure 3.4). Gaspra, an irregularly shaped S-type asteroid, is slighlty larger than the largest known ECAs.

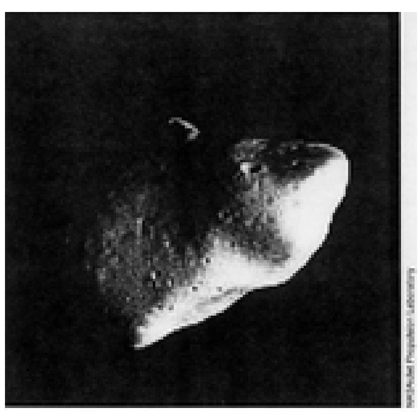

FIGURE 3.4. ***951 Gaspra, an S-type main-belt asteroid, was imaged by the Jupiter bound Galileo spacecraft on October 29, 1991 from a distance of about 16,200 km. Gaspra is an irregularly shaped object measuring about 18x11x10 km. It is the only asteroid yet studied by a spacecraft.***
NASA/JPL

It is particularly uncertain what the physical properties of comets (dead or alive) might be like. Only one comet has been studied in detail: Comet Halley, which was the target of several flyby spacecraft missions at the time of its last apparition in 1986. The nucleus of Halley (Figure 3.4) is irregular and dark, with an average diameter of about 10 km. Like other comets, it is made of a combination of ice(s), rocks, and dust, with much of the atmospheric outgassing near the Sun confined to discrete plumes or jets. In general, the physical configuration of comets is even more poorly understood than that of the small asteroids , and many comets have been observed to split under rather modest tidal and thermal forces. Their densities have not been measured but are thought to be about 1 g/cc, although many different estimates can be found in the scientific literature on comets. If we assume that comets are homogeneous and have roughly the same composition as Halley, then cometary nuclei are about half non-volatiles and half ices by weight. The non-volatiles include both silicates and organic materials. The primary ices (with percentages derived for Halley) are water (80 percent) and carbon monoxide (15 percent), plus lesser quantities of formaldehyde, carbon dioxide, methane, ammonia, and hydrocyanic acid.

FIGURE 3.5. ***The Nucleus of Comet Halley, as seen from the European Space Agency's Giotto spacecraft.***
copyrightMax-Planck Insitut fur Aeronomie, 1986. Courtesy of H.U. Keller.

The relationships between the brightness of comets, the size of their solid nuclei, and their distance from the Sun are complex and not fully understood. Two comets with known nuclear size (both about 10 km diameter), Halley and IRAS-Iraki-Alcock, differed by more than a factor of 100 in intrinsic brightness when near 1 AU from the Sun. Each well-observed intermediate or long period comet has exhibited a different pattern of activity as it approached and retreated from perihelion. Indeed, periodic comets exhibit different patterns of activity on different returns. Though seldom observed at solar distances greater than 5 AU, most long-period comets evidently become active somewhere between 5 and 10 AU. In some cases, weak intermittent activity has been observed at even greater distances from the Sun.

For a study of impacts, it is not essential to know a great deal about the physical nature of comets and asteroids. The most important properties are simply their mass and impact velocity, although it would make a difference if the projectile were double or multiple and easily came apart as it entered the atmosphere. However, any future program for intercepting and diverting an incoming comet or asteroid will require detailed knowledge of the configuration, density, cohesion, and composition of these objects. For these reasons, in addition to their significance for basic science, spacecraft missions to comets and near-Earth asteroids are essential. The first opportunity for a detailed study of a comet is provided by the NASA Comet Rendezvous and Asteroid Flyby mission (CRAF), now planned to study Comet Kopff in 2002 (CHECK). The opportunity for a similar study of a near-Earth asteroid will depend on approval of the NASA Discovery line of small planetary missions, the first of which is to be an asteroid rendezvous.

Next Chapter

6.1 Introduction

In the previous chapter we described a search strategy for the NEO survey in which we define the search operations to include both initial observations and verification on a second night. However, the uncertainty in the determination of the NEO orbit, and hence our ability to predict the object's future position, generally increase away from the period spanned by the observational data. If the positional data obtained during the discovery apparition are inadequate, then the uncertainty in the NEO's sky position during the next predicted apparition may be so large that the NEO cannot be recovered. The problem can be alleviated if the object is found in the existing file of observations of unidentified asteroids, but the object must otherwise be designated as lost, and it will remain lost until it is accidentally rediscovered. Clearly, we need to acquire sufficient data to minimize this loss of newly discovered objects.

An important part of the proposed survey involves the precise definition of NEO orbits, for this is a prerequisite to the identification of potentially hazardous objects. The critical first step in this process is to follow up each NEO discovery astrometrically, i.e., by tracking the object optically and/or with radar. Every NEO discovered should be followed astrometrically at least until recovery at the next apparition is assured. Further, we must develop explicit criteria for possibly hazardous ECAs, and any object that appears to fall into the "possibly hazardous" category on the basis of initial observations must be carefully tracked until an improved orbit determination allows a rigorous judgement as to its hazard potential.

In the case of an ECC, which cannot be tracked over several orbital periods, some uncertainty as to where (or even whether) it will strike the Earth may remain almost up to the time of impact. Smaller (Tungunska-class) ECAs may also require extensive tracking to determine their point of impact with sufficient accuracy (say 25 km) to permit rational judgements concerning countermeasures, such as the need to evacuate areas near the target. Finally, some uncertainty in the impact point will always remain due to lack of predictability of aerodynamic forces on the object in the Earth's atmosphere, especially if it breaks up during entry.

Apart from the astrometric follow-up observations, additional physical observations should be made to estimate the size and gross characteristics of the NEO. The rest of this chapter discusses various aspects of the follow-up process in detail.

6.2 Recognition and Confirmation

Immediately after the discovery and verification of an NEO, the principal need is to secure enough astrometric data (observations of position and velocity) that the orbit can be determined with some reasonable reliability. Modern asteroid-hunting practice is to measure carefully the positions of the objects in relation to the stars, and to do so on two nights in quick succession. Although the above procedure is mainly designed for main belt asteroids, its general features apply equally well to NEOs. The principal difference is that, because of its rapid motion, an NEO can generally be recognized as such on the night of its discovery, permitting the discoverer to plan for additional observations. In the case of an object moderately close to the Earth, the difference in perspective (parallax) arising from viewing points that are rotated about the center of the Earth (for example, at the same observatory but at times several hours apart) permits a rather accurate triangulation on the object's distance and hence contributes to the rapid determination of its orbit. In order not to interrupt the actual search process, it may be better to secure the additional initial-night observations with a different instrument or at a different site, although it is generally appropriate for the discoverer to take the responsibility for seeing that these observations are secured.

If an NEO is very close to the Earth, it is possible that enough information to compute a meaningful orbit can be obtained on a single night. Asteroid 1991 BA, which was observed eight times over only a five-hour interval, is an excellent example of this. If an initially computed orbit bears a resemblance to that of the Earth, however, it is quite probable that the object is an artificial satellite. There do exist artificial satellites in highly eccentric orbits with apogees at and even beyond the orbit of the Moon. In the recent case of tiny NEO 1991 VG, the earthlike orbit was verified as more observations became available, thereby introducing the troublesome possibility that this was an uncatalogued artificial object that had completely escaped from the

Earth's gravity long ago but that was now returning to the Earth's vicinity. As the quantity of "space junk" increases, similar problems are likely to recur.

The majority of the ECAs discovered will be visible only for relatively short time intervals because, being small, they must be close to Earth to be detectable. Indeed, the simulations discussed in Chapter 5 show that in a 25-yr survey covering the standard 6,000 square degree region to V = 22, the distance of closest approach of ECAs larger than 0.5 km diameter peaks at only about 50 lunar distances. The number of monthly observing runs during which ECAs larger than 0.5 km diameter can be detected in the standard survey region is shown as a function of V in Figure 6-1. At V= 18, 20, 22, and 24, the percentages of ECAs detected in only one run are 59, 41, 20, and 4 percent, respectively. The median numbers of runs in which ECAs are detectable are 1, 2, 4, and 9, respectively, although a few are reobservable almost 30 times. At a diameter threshold of 1 km and for faint magnitudes, the percentages of ECAs observed in only one run are a factor of two smaller, and the median numbers of runs are increased by about 50 percent.

In the strategy described in Chapter 5, we did not directly address the use of the survey telescopes to obtain follow-up astrometric positions near the time of discovery. If follow-up observations were made out to, say, 60 deg longitude from opposition, the percentage of ECAs larger than 0.5 km seen only once to V = 22 would be reduced from 20 to 12 percent. Even greater protection against loss would be afforded by a follow-up strategy in which ECAs discovered were reobserved as long as possible in any accessible region of the dark sky. The question of strategy for this follow-up work needs further study, with the results depending on the availability of other supporting telescopes for astrometric observations.

Since losses after observation in one monthly run can be reduced to small numbers, it is probable that, for deep ECA surveys, follow-up can largely be ignored in favor of the linkage of detections from one run or one apparition to another. In general, such linkage can be achieved unambiguously provided observations are not too sparse. However, care must be taken not to lose the very fast-moving ECAs that may be most hazardous to Earth. Also, because of the large numbers of small ECAs that will be discovered, selection must be made, at least in part, on the basis of the diameter threshold. Both considerations call for a rapid estimate of the diameters of all ECAs discovered near the magnitude limit. To achieve this, the observed brightness can be combined with the distance gauged by means of diurnal parallax. Preference in such work should be given the those objects that appear to be true ECAs, especially those that might pose some threat based on initial orbit calculation.

6.3 Optical Astrometry

For a typical NEO, astrometric follow-up is essential. Much of the follow-up astrometry is most conveniently and efficiently accomplished using conventional reflecting telescopes fitted with CCDs. If conventional reflectors are used, they should generally be in the 1- to 2-m aperture range, although larger telescopes should certainly be considered for following up very faint discoveries. A set of semi-dedicated observatories is preferable to a single dedicated observatory (or one in each hemisphere), if only for reasons of weather and availability of observers, and there are certainly times when the more-or-less continuous coverage that may thereby be possible can be very useful.

Existing facilities currently involved with astrometric follow-up of NEOs are listed below in order westward from the principal U.S. discovery sites (the 0.46-m Schmidt at Palomar and the Spacewatch 0.9-m reflector at Kitt Peak), separately for each hemisphere:

Northern hemisphere:

Victoria, B.C., Canada (0.5-m reflector with CCD); Mauna Kea, Hawaii (2.2-m U Hawaii reflector + 3-m NASA IRTF with encoders); Japan (no professional but much amateur activity); Kavalur, India (fledgling Spacewatch program); Kitab, Uzbekistan, and Crimean Astrophysical Observatory, Ukraine (0.4-m astrographs; coordinated by the Institute for Theoretical Astronomy, St. Petersburg, Russia); Klet, Czechoslovakia (0.6-m Maksutov; currently no e-mail communication but should become possible via Prague); Western Europe (not much professional activity, but possibilities at Caussols, France, 0.9-m Schmidt, and La Palma, Canaries, 2.2-m reflector with CCD); Oak Ridge, Massachusetts (1.5-m reflector with CCD); Lowell Observatory, Arizona (1.1-m and 1.8-m reflectors with CCD). Other possibilities include the 1.3-m Schmidt at Tautenburg, Germany, and telescopes at the Bulgarian National Observatory, but these are not currently involved with NEOs, and rapid communication is a problem.

Southern hemisphere:

Mount John Observatory, New Zealand (0.6-m reflector, conversion to CCD in progress); Siding Spring, N.S.W., Australia (U.K. 1.2-m Schmidt, 0.5-m Uppsala Southern Schmidt, 1.0-m reflector with CCD); Perth, W.A., Australia (occasional use of 0.3-m astrograph or 0.6-m reflector); European Southern Observatory, Chile (occasional use of 1.0-m Schmidt, 0.4-m astrograph or 1.5-m reflector). Also there would seem to be a need for participation in southern Africa and eastern South America.

6.4 Radar Astrometry

Radar is also an essential astrometric tool, yielding both a direct range to an NEO and the radial velocity (with respect to the observer) from the doppler-shifted echo (Yeomans and others 1987; Ostro and others 1991). Since most NEOs are discovered as a result of their rapid motion on the sky, these objects are then generally close to the Earth; radar observations are therefore often immediately possible and appropriate. However, radar observations do not become feasible until the object's expected position can be refined (from optical astrometry) to better than about 1 arcmin, and an accuracy of 10 arcsec or better is preferable. A single radar detection has a fractional precision that is two or three orders of magnitude beyond that of optical astrometry, so the inclusion of radar data with the optical data in the orbit solution can quickly and dramatically reduce the future ephemeris uncertainty.

The principal radar instruments are currently those at Arecibo, Puerto Rico, and Goldstone, California. There may also be possibilities at Effelsberg, Germany, Parkes, N.S.W., Australia, and Yevpatoriya, Ukraine Since radars are range limited, radar-detectability windows are narrow, but both Arecibo and Goldstone are being upgraded to enlarge their current windows. There is a clear need for a comparable facility in the southern hemisphere, and some preliminary planning has been done for an "Arecibo-class" radio telescope in Brazil which could also be used as a radar.

The inclusion of radar data in the orbital solutions would allow an NEO's motion to be accurately integrated forward for a few decades (or centuries) to assess the likelihood of future Earth impacts. With optical data alone, such an assessment requires an observational span of several years, which may or may not be possible from the inspection of old photographic plates. The addition of radar data to the orbital solution may allow reliable extrapolations of the object's motion to be made within only days of discovery.

There has hitherto always been a time interval, at least several days long, between discovery and the initial radar work. If the first radar ephemeris is found to have very large delay or doppler errors, the initial radar astrometry is used to generate a second-generation radar ephemeris to enable finer-precision delay or doppler astrometry (by at least a factor of ten) than would have been possible with the first radar ephemeris. This bootstrapping process would be much more efficient than it currently is if a capability to do the computations existed at the radio telescope itself. Ideally, one could input the first measurements of doppler and delay into a program on a computer at the site, generate an improved ephemeris within an hour of initial detection, and proceed immediately to high-resolution ranging. The existence of on-site ephemeris generating capability would be essential if the astrometry that does the critical shrinking of the pointing uncertainty becomes available at the same time as the object enters the radar window, or with an NEO that comes so close that it traverses the telescope's declination-distance window in one day (like comet IRAS-Araki-Alcock at Arecibo in 1983).

6.5 Physical Observations

The impact energy of an NEO that actually hits the Earth depends on both its velocity and its mass. Knowledge of the orbit provides only the velocity, not the mass. The latter quantity can be estimated only from physical observations. If astrometric observations are made with a photometric device, such as a CCD, they can also provide information about the most basic of physical parameters, namely, the brightness of the object. In the case of a bright comet, measurements of the brightness will almost certainly include a strong contribution from the atmosphere, whereas what is needed is isolation of the solid nucleus, something that can be satisfactorily attempted only when the comet is farther from the Sun.

Although an asteroid's brightness is correlated with its size, the known range of asteroid surface reflectivities spans a factor of 20, which leads to a large uncertainty in the volume. The range of densities of asteroids can be inferred from their bulk compositions, which may in turn be suggested by measurements of surface composition.. If only a brightness measurement is available, the deduced mass of the object, and therefore the potential impact energy, can be uncertain by a factor of a hundred. Additional uncertainty arises from the fact that asteroid brightnesses vary as they rotate, sometimes by more than a factor of five.

Measurements of the relative reflectivity of an asteroid at a variety of wavelengths (its spectral reflectivity) can place the object in one of several known taxonomic classes and therefore reduce the uncertainty in the surface reflectivity. At the same time, the composition of the object is constrained, leading to an improved estimate of the bulk density. In a minimal effort, the use of three filters, appropriately chosen to sample spectral features in the ultraviolet and infrared regions, should be employed. With additional filters, greater diagnosticity can be achieved, with a corresponding improvement in reflectivity and composition estimates. With a minimal filter set, however, the range of potential impact energies can be reduced to a factor of about ten.

Radar observations are the only source of spatially-resolved measurements from the ground and hence provide the only source of direct information about an NEO's shape. Moreover, radar can also supply constraints on size that are highly reliable if the echoes are strong enough. Radar also provides some information about the composition and roughness of an NEO's surface.

Even single-color photometry permits a rotation period to be determined, and radar can then provide the spin-pole direction. The angular momentum of a potential hazard can therefore be calculated, and this may be an important consideration in deciding on the technique to be used for dealing with the hazard. In the case of a comet, the detection of persistent cyclic variations in the brightness of the condensation about a stable mean is probably an indication that the bare nucleus has been detected.

That NEOs differ greatly in composition is also evident from a comparison of the effects of encounters. Although the bodies that produced Meteor Crater in Arizona 50,000 years ago and the

Tunguska event in Siberia 84 years ago are both thought to have been in the rough size range 50-100 m, one produced a crater that is still very obvious while the other apparently exploded high above the ground, produced no crater, but levelled trees over a much larger area. Knowledge of the likely composition can also play a prominent role in establishing the ameliorative action that might to be taken in the case of a predicted impact.

One could argue that it is not necessary to make physical observations until an object on a collision course has actually been detected. This may not be a prudent course of action, however, for the following reasons. (1) The possibility exists that there will be no further opportunity to study the object in question sufficiently in advance of a collision to provide the necessary information on the potential impact energy and on how to deal with the object. (2) Discoveries of NEOs are often made when they are unusually close to the Earth, and physical observations can be performed more efficiently and with higher precision at these times. (3) We need to learn more about the full range of NEO compositions and structural properties, which are poorly known at present, to plan possible strategies for deflection of these objects in case of a predicted impact. (4) There are significant scientific and possible future commercial benefits that can result from the study of a sizable portion of the NEO population, including the identification of objects with resource potential (substantial sources of water or of nickel-iron and other heavy metals), the providing of selection criteria for possible future spacecraft missions to such objects, the understanding of the link between terrestrial meteorites and the asteroid belt, and important information regarding the origin (cometary versus asteroidal, for example) of these objects.

6.6 Survey Clearinghouse and Coordination Center

Much of the discussion in this chapter has been in the context of current practice.for NEO discoveries. However, the proposed new search strategy described in Chapter 5 means that future NEO discoveries may take place up to 5 magnitudes, or 100 times, fainter than at present. When searches routinely reach magnitude 22 there should be about 500 new NEO candidates each month. With careful organization of the discovery searches, however, the astrometric follow-up data could all be obtained with the same telescopes involved in the discovery. In particular, thought should be given to ensuring that the relevant fields are automatically recorded with a large time separation on either the first or the second night in order to make a parallactic determination of a crude orbit. Month-by-month opposition scanning should also allow, at least in principle, the correct identification of subsequent images of each NEO, but in order to ensure success it would probably be desirable to perform the discovery and confirmation regimen twice during each monthly run.

Bright time (that is, time when the Moon is up) on the discovery telescopes could also be used for physical observations, but radar observations would presumably have to be restricted to close passages by the Earth. Sampling of the physical properties of the smaller NEOs would be important in case they are systematically different from those of the larger NEOs and the main belt asteroids. However, their faintness makes certain observations difficult, so that a large dedicated follow-up telescope with special instrumentation would prove more effective for some physical observations than the survey telescopes themselves.

The dramatic increase in the rate of discovery of NEOs will require considerable extension of the current system for keeping track of these objects and disseminating information about them. Hitherto these functions have principally been carried out by the International Astronomical Union's Central Bureau for Astronomical Telegrams and Minor Planet Center, which since 1978 have been operating together at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, under the direction of B. G. Marsden. The Minor Planet Center currently deals with asteroid discoveries (primarily main belt objects) at an annual rate of a few thousand. With the prospect of discovering a thousand NEOs alone in a month, rather than a year, augmentation of the Minor Planet Center's capabilities will be necessary. Procedures for rapidly checking, identifying, computing orbits and providing appropriate ephemerides for new discoveries are already in place, but future enhancement will require acquisition of faster computers and the employment of additional personnel. The future NEO survey clearinghouse would also be undertake the task of actually planning the observations at the various sites, collecting the observations from the sites, and coordinating further observations to cover fields missed by bad weather and to ensure proper follow-up in specific cases.

Further development of procedures and construction and maintenance of software must also be an important component of the work of the survey clearinghouse. For comets and asteroids, the computation of an orbit and ephemeris should include an estimate of the uncertainty in the NEO's location as a function of time, that is, the "positional error ellipsoid." (Yeomans and others 1987; Muinonen and Bowell 1992). (This is less easily done in the case of comets because of the existence of nongravitational effects that can at best be modelled in a semi-empirical manner.) By projecting the error ellipsoid into the future, one can quantify the likelihood that an NEO will be recoverable, and one can also assess the uncertainty in an Earth-asteroid distance for any future close approaches. Such software will also (1) help to expedite verification of newly discovered objects as NEOs, (2) provide the basis for prioritizing NEOs for follow-up astrometry, both to avoid losing objects and to optimize the use of telescope time and personnel, and (3) permit the reliable identification of NEOs on very close-approach trajectories and the appropriate hazard assessment.

For each newly discovered NEO, data files will have to be established to catalog discovery data and follow-up observations, both astrometric and physical. Orbits and associated error analyses will be required for each object to identify close Earth approaches in the immediate future and to establish optimum observation times for securing the object's orbit and ensuring its recovery at subsequent observation opportunities. Once the need for follow up observations has been established and the optimal observation times determined, the clearinghouse would notify the appropriate people capable of making the required observations and provide them with all the information required to utilize efficienyly the limited amount of available telescope time. Recently, a NASA center for some of these clearinghouse activities has been established at the Jet Propulsion Laboratory.

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8.1 The Necessity of International Cooperation

That the hazard posed by NEO's is a problem for all humankind hardly needs repeating. The likelihood of a particular spot being the target of an impact is independent of its geographic position, so that we are all equally at risk. Further, each person on the face of the planet would be severely affected by a large impact, as discussed in Chapter 2.

The problem is thus international in scope; it is also international in solution. To obtain the spatial and temporal coverage of the sky that is required by the search program outlined in Chapter 7, a wide geographical coverage of optical observatory sites is essential. Even if these sites were limited to six, still at least five countries would likely be involved directly as telescope hosts. However, the number of nations actually involved would be larger than this. If Australia were one site then most likely the Anglo-Australian Observatory would be the organization acting as host, implying British involvement. Similarly a site in India, where a Spacewatch-type instrument is currently being developed, might involve a continuation of direct U.S. collaboration. Some of the best observatory sites in the southern hemisphere are in Chile, and if plans go ahead for the development of a large southern radar in Brazil, again the number of countries increases. The need for international cooperation is obvious, and rapid and efficient international communication through a central agency is a requirement.

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8.2 Current International Efforts

The independent character of the scientific endeavor as well as

limited funding resources has resulted in a current program to find and track NEOs that is quite fragmentary. Generally it has been possible, in recent years, for discoveries made by one team to be followed up by other observers, but this has not always been the case, allowing some newly-discovered NEOs to be lost. For the program planned here this must not be allowed to occur, emphasizing the need for an international effort with close cooperation and priorities to be set by a central organization. The present level of our knowledge of NEO's has only been possible because of the services of the staff of the Central Bureau for Astronomical Telegrams and the Minor Planet Center (Cambridge, Massachussetts) who coordinate the analysis of observations of NEO's and make every effort to ensure that sufficient coverage occurs. A continuation of such a service on a larger scale will be necessary if the proposed program is to be brought to fruition.

There have in the past been some efforts made at formally organizing a search program on an international scale, quite apart from the informal links and communications made possible by personal contacts. The most prominent of these organizations has been INAS, the International Near-Earth Asteroid Survey, coordinated by E.F. Helin (Helin and Dunbar, 1984, 1990). INAS has resulted in increased cooperation between observatories in various countries, and hence an increase in the discovery rates. Apart from the U.S., scientists from the following countries have been involved in INAS: France, Italy, Denmark, Sweden, Bulgaria, Czechoslovakia, Yugoslavia, Germany, China, Japan, Russia, Ukraine, United Kingdom, Canada, Australia, and New Zealand.

The major thrust of INAS has been to coordinate the efforts of the large wide-field photographic instruments with regard to temporal and sky coverage. An immediate expansion of this effort can increase the current discovery rate, thus providing valuable information on the true statistical nature of the NEO population and associated impact hazards before the full network of survey telescopes becomes operational. Such a program will also serve as a training ground for new personnel and provide valuable experience with improved international communication and coordination.

A Spacewatch-type telescope is currently under development in India with the joint support of the U.S. Smithsonian Institution and the Government of India. Another international effort is being proposed by the Institute for Theoretical Astronomy in St. Petersberg, Russia, under the direction of A.G. Sokolsky. This group organized an international conference The Asteroid Hazard in October 1991, which endorsed the idea that NEOs "represent a potential hazard for all human civilization and create a real threat of regional catastrophes"

and noted "the necessity of coordinated international efforts on the problem of the asteroid hazard." This group has asked the Russian Academy of Science to support the formation of an International Institute on the Problem of the Asteroid Hazard under the of the International Center for Scientific Culture -- World Laboratory, and they propose to coordinate asteroid search and follow-up observations in central and eastern Europe.

8.3 Funding Arrangements

If this international survey program is to succeed, it must be arranged on an inter-governmental level. To ensure stability of operations, the NEO survey program needs to be run by international agreement, with reliable funding committed for the full duration of the program by each nation involved.

There are good reasons for the funding to be expected to be derived from all nations directly involved in the program. First, most countries usually want to provide for their own defense rather than to rely upon another or others to do this for them, so we may anticipate that nations in the world-wide community will wish to each play their own part in defending the planet. Second, although this program is large compared with present NEO search efforts, in fact it would be of quite a small overall budget. Thus it is possible for nations to make a significant contribution with little expense whereas it would not be possible for them to buy into a large space project, or even the construction of a ground-based 10-meter-class astronomical telescope. For example, there is a small group in Uruguay who study dynamical aspects of NEO's, and they could provide an essential service to the program; or the telescopes available for follow-up work in New Zealand or Romania could be utilized, and thus those nations gain prestige on the international scene at little expense. Involvement in space programs (which this program is, in essence) is generally viewed favorably by the populace of most countries. Third, this program may be a significant technology driver, so that money spent on the investigation and development of new technologies can be viewed as an investment rather than an expenditure.

With the encouragement of the United States as prime mover, the

funding for national sectors of the overall international search program should be attainable locally. For example, Australia and the United Kingdom, through their joint observatory in Australia, could immediately boost the current discovery rate to about 100 per year using existing equipment and technology given supplementary funding from those countries of the order of $0.25 million per year, although we would anticipate that this effort would be superseded by the introduction of CCD detectors within five years. Photographic searches currently being carried out in the United States might require a similar boost in funds, with a concomitant boost in discovery rate resulting, and the Spacewatch effort could also be significantly expanded by approval for the upgrade to 1.8-m aperture and funding to run the camera on more than eighteen nights per month.

8.4 International Sanction

The astronomical program outlined in this report already has the support of various international bodies. There is a burgeoning awareness in the astronomical community that the NEO impact hazard is a topic that requires attention for reasons other than altruistic scientific pursuit. At the 1991 General Assembly of the International Astronomical Union held August 1 in Buenos Aires, Argentina, the following resolution was passed:

> The XXIst General Assembly of the International Astronomical Union,
>
> Considering that various studies have shown that the Earth is subject to occasional impacts by minor bodies in the solar system, sometimes with catastrophic results, and
>
> Noting that there is well-founded evidence that only a very small fraction of NEO's (natural Near-Earth Objects: minor planets, comets and fragments thereof) has actually been discovered and have well-determined orbits,
>
> Affirms the importance of expanding and sustaining scientific programmes for the discovery, continued surveillance and in-depth physical and theoretical study of potentially hazardous objects, and

Resolves to establish an ad hoc Joint Working Group on NEOs, with the participation of Commissions 4, 7, 9, 15, 16, 20, 21 and 22, to:

1. Assess and quantify the potential threat, in close interaction with other specialists in these fields
2. Stimulate the pooling of all appropriate resources in support of relevant national and international programmes;
3. Act as an international focal point and contribute to the scientific evaluation; and
4. Report back to the XXIInd General Assembly of the IAU in 1994 for possible further action.

The Working Group, to be convened by A. Carusi of Italy, comprises the following scientists:

A. Bazilevski (USSR)
A. Carusi (Italy)
B. Gustafson (Sweden)
A. Harris (USA)
Y. Kozai (Japan)
G. Lelievre (France)
A. Levasseur-Regourd (France)
B. Marsden (USA)
D. Morrison (USA)
A. Milani (Italy)
K. Seidelman (USA)
G. Shoemaker (USA)
A. Sokolsky (USSR)
D. Steel (Australia/UK)
J. Stohl (Czechoslovakia)
Tong Fu (China)

This Working Group was selected not only on the basis of the geographical spread of persons active in the general area, but also in terms of expertise in distinct areas of the necessary program (e.g. celestial mechanics, generation of ephemerides, physical nature of NEO's, dynamics of same, relationship to smaller meteoroids and interplanetary dust). Five of these 16 individuals are also members of the NASA International NEO Detection workshop, ensuring appropriate continuity of effort.

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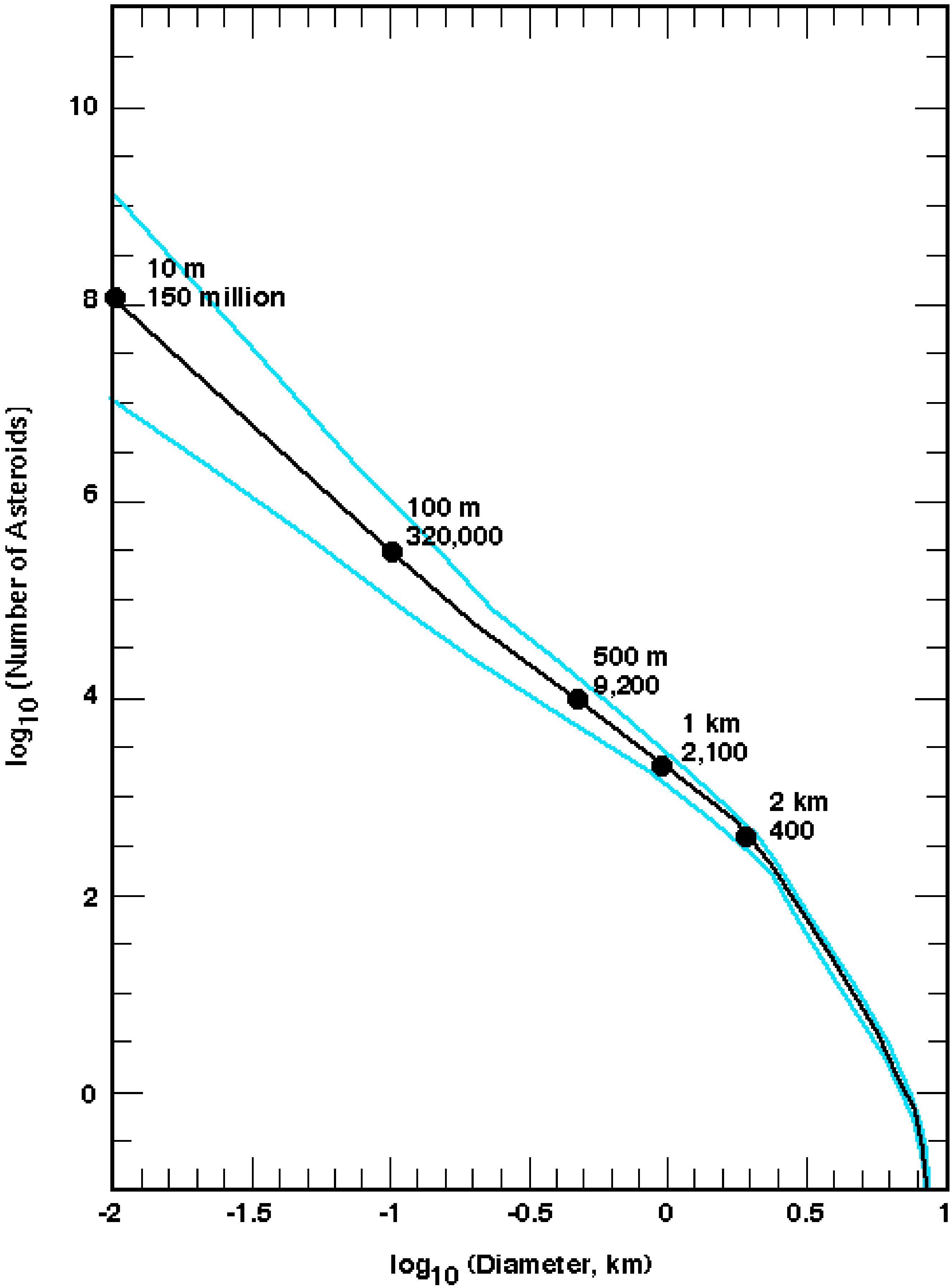
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150 million
100 m
320,000
500 m
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1 km
2,100
2 km
400
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8
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-1
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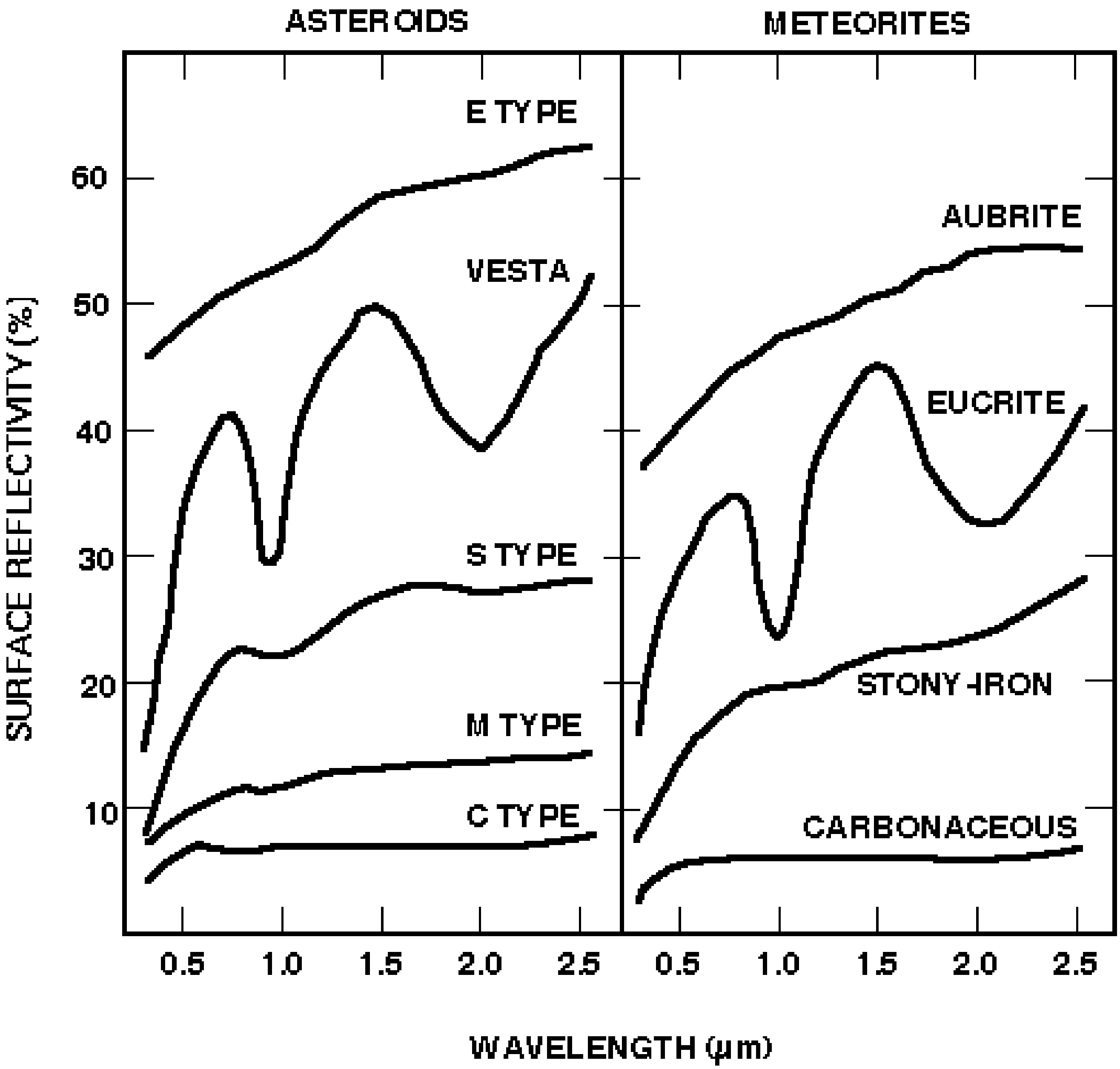
1
log10 (Number of Asteroids)
log10 (Diameter, km)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E TYPE
VESTA
S TYPE
M TYPE
C TYPE
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EUCRITE
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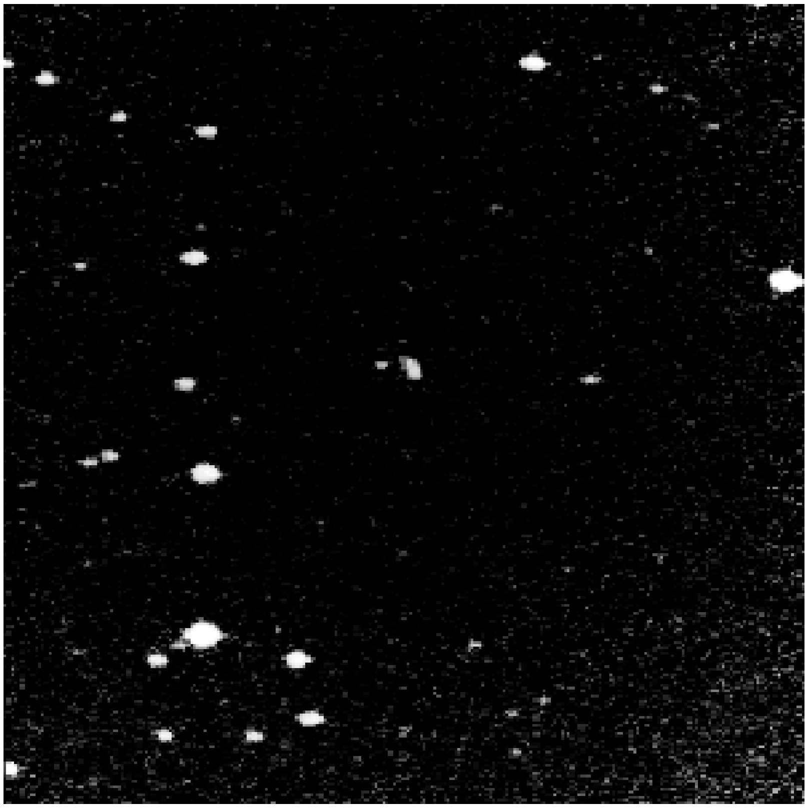
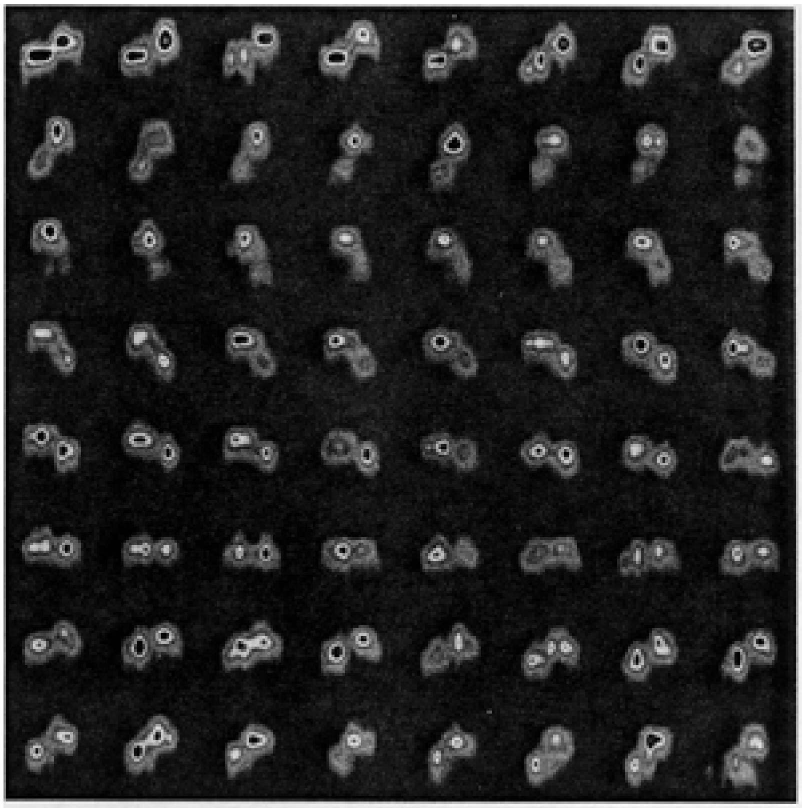
WAVELENGTH (μm)





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4.1 Introduction

The first Earth-crossing asteroid, Apollo, was discovered photographically in 1932 at Heidelberg and then lost until 1973. In the following decades only a handful of additional ECAs were discovered, and many of these were temporarily lost also. Not until the 1970s were regular searches initiated, using wide-field Schmidt telescopes of modest aperture. Some of these photographic survey programs continue today with steadily increasing discovery rates. In the early 1980s these photographic approaches were supplemented by a new technique of electronic CCD scanning implemented at the University of Arizona, and by the late 1980s this more automated approach was also yielding many new discoveries. Even today, however, the total worldwide effort to search for NEOs amounts to fewer than a dozen full-time-equivalent workers! In this chapter we briefly review the history and current status of both the photographic and CCD searches.

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4.2 Photographic Search Programs

Photographic techniques

The overwhelming majority of discoveries of near-Earth asteroids (and increasingly of comets) has been obtained from photographic searches carried out with wide-field Schmidt telescopes. The bulk of discoveries has been made in the last decade, and the rate of discovery is rapidly increasing. This increase is due in part to improved technology but principally to increased interest within the astronomical community.

To date the two most productive photographic teams in this field have been those directed by E. F. Helin and E.M. Shoemaker. Most of their work has been done using the 0.46-m Schmidt telescope at Palomar Observatory, California. Observing programs on three large Schmidt telescopes located in France, Chile,and Australia have also contributed but rather sporadically, as has work carried out with a narrower-field astrograph in Ukraine. A new successful program has recently been started on the UK Schmidt in Australia. The three main photographic programs now in operation are described briefly below.

Various techniques are used to detect and measure NEOs, but the search process must be carried out very soon after the exposure in order to permit rapid followup. In some programs the films are exposed in pairs with a gap in time between the first and subsequent exposure, then scanned with a specially built stereo comparator. Images which move noticeably between the first and second exposure may be detected in this way. Alternatively, a visual search can be carried out using a binocular microscope, and trailed images (produced by the motion of the NEO during the time exposure) are noted. The angular velocity may be inferred from the motion between exposures or in the case of a single exposure, from the trail length (Fig. 4-1). Selection of potential NEOs is carried out on the basis of this angular velocity, and only those objects with anomalous motions are followed up to determine precise orbits.

A variety of photographic emulsions have been used in NEO searches, but the most effective have been the IIIa-type emulsions coated on glass from Kodak, introduced twenty years ago, and a panchromatic emulsion coated on a film base released in 1982, again from Kodak. The new film (4415) has been particularly useful and is now the emulsion of choice for this work.

Planet-Crossing Asteroid Survey (PCAS)

The PCAS survey for Earth-crossing and other planet-crossing asteroids was initiated by E.F. Helin and E.M. Shoemaker in 1973 and is now directed by Helin. It is the longest running dedicated search program for the discovery of near-Earth asteroids and is carried out with the 0.46-m Schmidt telescope at Palomar Observatory in California. Early in the survey, about 1000 square degrees of sky were photographed each month. In the last ten years, the use of fast film has allowed shorter exposures leading to greater sky coverage. This fact, in combination with a custom-made stereo-microscope, has resulted in a five-fold increase in the discovery rate over the early years of the program. Using the stereo pair method, up to 4000 independent square degrees of sky can be photographed per month. This program has been particularly successful in getting out early alerts on new discoveries so physical observations can be obtained during the discovery apparition. There has also been an organized international aspect to this program, called the International Near-Earth Asteroid Survey (INAS), which attempts to expand the sky coverage and the discovery and recovery of NEAs around the world.

Palomar Asteroid and Comet Survey (PACS)

A second survey with the Palomar 0.46-m Schmidt was begun by E.M. and C.S. Shoemaker in 1982 and has continued with the collaboration of H.E. Holt and D.H. Levy. About 3000 square degrees of sky are photographed each month. Both the PACS and PCAS programs center their sky coverage at opposition and along the ecliptic and attempt to cover as much sky as possible in every 7-night observing run at the telescope. The two programs combined produce about 6000 independent square degrees of sky coverage per month.

Anglo-Australian Near-Earth Asteroid Survey (AANEAS)

The AANEAS program began in 1990 under the direction of D.I. Steel with the collaboration of R.H.McNaught and K.S.Russell using a visual search of essentially all plates taken with the 1.2-m U.K. Schmidt Telescope as part of the regular sky survey. Up to 2500 square degrees are covered each month to a limiting stellar magnitude near 22.

4.3 The Spacewatch CCD Scanning Program

An alternative to photographic search programs was developed at the University of Arizona under the name "Spacewatch" by T. Gehrels in collaboration with R. MacMillan, D. Rabinovich, and J. Scotti. This system makes use of a CCD detector instead of photographic plates. It differs from the wide-field Schmidt searches in scanning smaller areas of sky but doing so to greater depth. In 1981, the Director of the University of Arizona Observatories made the Steward 0.9-m Newtonian reflector on Kitt Peak available, and initial funding for instrument development was obtained from NASA. By 1983 Spacewatch had a 320 x 512 pixel CCD in operation, which was too small for discovery of near-Earth asteroids on that telescope, but was exercised in order to get experience with CCD modes of operation. Later this was upgraded to a 1048x1048 pixel CCD.

The basic construction and operation of the CCD are ideal for scanning. It is referred to as the "scanning mode"; in older literature it is called Time Delay Integration (TDI). The scanning is done by exactly matching the rate of transfer of the charges, from row to row of the CCD chip, with the rate of scanning by the telescope on the sky. A basic advantage of scanning is the smooth continuous operation, reading the CCD out during observing, compared to stop-and-go resetting the telescope for each exposure and waiting for the CCD to be read out before the next exposure can be started. Another advantage of scanning is that the differences in pixel sensitivity are averaged out, and two-dimensional "flat fielding" calibration is therefore not needed.

As each line of the CCD image is clocked into the serial shift register, it is read out by the microcomputer and passed on to the workstation. There the data are displayed, searched for moving objects, and recorded on magnetic tape. As each moving object is discovered (Fig. 4-2), from the three repeated scan regions of about 30 minute length, its image is copied to a separate "gallery" window for verification by the observer. Some five years of computer programming went into this system.

Currently this Spacewatch system is discovering approximately as many NEOs as the photographic surveys. As a consequence of its more sensitive detector, it also tends to discover more smaller objects, including three objects found in 1991 that are only about 10 m in diameter. Substantial increases in capability are proposed with a new telescope of larger aperture (1.8 m) to replace the current Spacewatch telescope in the same dome.

4.4 Potential of Current Programs

Later Chapters of this Report describe a survey program based on a new generation of scanning telescopes. However, there is still excellent work to be done with current instruments during the transition to the new survey. The near-term potential of photographic techniques may be considered in the following context. With the provision of about $1 million capital costs and $1 million per year operating expenses it would be possible to boost the current worldwide photographic discovery rate from about 20 per year to 100 per year. Similarly, an upgrade of the Spacewatch CCD scanning system to 1.8-m aperture would more than double the output of this system, and still greater gains are possible utilizing advanced, large-format CCDs. This instrument can also be used as a test-bed for new NEO survey techniques such as use of CCD arrays, optimizing of scanning strategies, and refinement of automated search software.

By the time large search telescopes with CCD detectors become available later in this decade it would be possible to have a sample of at least 1000 NEO's with well determined orbits. From this sample, which should include about 10 percent of the larger bodies, we will gain a much better idea of the physical properties and dynamical distribution of the total population. Such information will be invaluable in optimizing the search strategy of the large new telescopes. In addition, the operation of the large CCD search facilities will require trained personnel and a complex organization to utilize them to the fullest extent, and expansion of current programs can provide the experienced staff that will be required if and when the full survey begins operation.

We assume in the following facility overview that wide-field photography will continue in a substantially productive manner for a number of years. CCD work is expected at the Spacewatch telescope on Kitt Peak in Arizona (with proposed upgrade to 1.8-m aperture) and with the French OCA Schmidt and the Palomar 0.46-m Schmidt, both of which are proposed for conversion to CCD operation.

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9.1 Overview

Concern over the cosmic impact hazard motivated the U.S. Congress to request that NASA conduct a workshop to study ways to achieve a substantial acceleration in the discovery rate for near-Earth asteroids. This report outlines an international survey network of ground-based telescopes that could increase the monthly discovery rate of such asteroids from a few to as many as a thousand. Such a program would reduce the time-scale required for a nearly complete census of large Earth-crossing asteroids (ECAs) from several centuries (at the current discovery rate) to about 25 years. We call this proposed survey program the Spaceguard Survey (borrowing the name from the similar project suggested by science-fiction author Arthur C. Clarke nearly 20 years ago in his novel *Rendezvous with Rama*).

In addition, this workshop has considered the impact hazards associated with comets (both short-period and long-period) and with small asteroidal or cometary objects in the tens of meters to hundreds of meters size range. The object is not elimination of risk, which is impossible for natural hazards such as impacts, but reduction of risk. Emphasis, therefore, is placed upon the greater hazards, in an effort to define a cost-effective risk-reduction program. Below we summarize our conclusions with respect to these three groups of objects: ECAs, comets, and small (Tunguska-class) objects.

1) Large ECAs *(diameter greater than 1 km, impact energy greater than a100,000 megatons).* These objects constitute the greatest hazard, with their potential for global environmental damage and mass mortality. About two thousand such objects are believed to exist in near-Earth space, of which fewer than 10 percent are now known. Between a quarter and a half of them will eventually impact the Earth, but the average interval between such impacts is long -- more than 100,000 years. While some of these objects may break up during entry, most will reach the surface, forming craters if they strike on the land. On average, one ECA in this size range passes between the Earth and the Moon every few decades.

The proposed Spaceguard Survey deals effectively with this class of objects. Telescopes of 2- to 3-m aperture can detect them out to a distance of 200 million kilometers. Since their orbits bring them frequently within this distance of the Earth, a comprehensive survey will discover most of them within a decade and can achieve near completeness within 25 years. Specifically, the survey modeled here, covering 6000 square degrees of sky per month to magnitude V = 22, is calculated to achieve 91 percent completeness for potentially hazardous ECAs in 25 years. The most probable outcome of this survey will be to find that none of these objects will impact the Earth within the next century, although a few will need to be followed carefully to ensure that their orbits do not evolve into Earth-impact trajectories. In the unlikely case (chances less than 1 percent) that one of these ECAs poses a danger to the Earth over the next century or two, there will be a warning of at least several decades to take corrective action to deflect the object or otherwise mitigate the danger.

2. Comets. Comets with short periods (less than 20 years) will be discovered and dealt with in the same manner as the ECAs described above; they constitute only about 1 percent of the ECA hazard in any case. However, comets with long periods (more than 20 years), many of which are entering the inner solar system for the first time, constitute the second most important impact hazard. While their numbers amount to only 5 to 10 percent of the ECA impacts, they approach the Earth with greater speeds and hence higher energy in proportion to their mass. It is estimated that as many as 25 percent of the objects reaching the Earth with energies in excess of 100,000 megatons are long period comets. On average, one such comet passes between the Earth and Moon per century, and one strikes the Earth every few hundred thousand years.

Since long-period comets do not (by definition) pass frequently near the Earth, it is not possible to obtain a census of such objects. Each must be detected on its initial approach to the inner solar system. Fortunately, comets are much brighter than asteroids of the same size, as a consequence of outgassing stimulated by solar heating. Comets in the size range of interest will generally be visible to the Spaceguard Survey telescopes by the time they reach the asteroid belt (500 million km distant), providing several months of warning before they approach the Earth. However, the short time-span available for observation will result in less well-determined orbits, and hence greater uncertainty as to whether a hit is likely; there is a greater potential for "false alarms" with comets than asteroids. Simulations carried out for this report indicate that only 35 percent of Earth-crossing intermediate- and long-period comets (ECCs) greater than 1 km in diameter will be detected with at least three months warning in a survey of 6000 sq degrees per month. By increasing the area of the survey to include the entire dark sky, as many as 77 percent could be detected.. Increasing telescope aperture to reach fainter magnitudes (V = 24) improves the discovery rate still further. Because of the continuing hazard from comets, which may appear at any time, the cometary component of the Spaceguard Survey should be continued even when the census of large Earth-crossing asteroids is essentially complete.

3. Smaller Asteroids, Comets, and Meteoroids *(diameters from about 100 m to 1 km; energies from 20 to 100,000 megatons).* These impacts are below the energy threshold for global environmental damage, and they therefore constitute a smaller hazard in spite of their more frequent occurrence. Unlike the large objects, they do not pose a danger to civilization. The nature of the damage they cause depends on the size, impact speed, and physical nature of the impacting object; only a fraction of the projectiles in this size range will reach the surface to produce a crater. However, detonation either at the surface or in the lower atmosphere is capable of severe local damage, generally on a greater scale than might be associated with a large nuclear weapon. Both the Tunguska (1908) and Meteor Crater impacts are small examples of this class. The average interval between such impacts for the whole Earth is a few centuries; between impacts in the inhabited parts of the planet is a few millennia; and between impacts in densely populated or urban areas is of the order of 100,000 years. About 300,000 Earth-crossing objects probably exist in this size range, with several passing between Earth and Moon each year.

The Spaceguard Survey will discover as many hundreds of objects in this size range every month. By the end of the initial 25-year survey, it will be possible to track the orbits of as many as 100,000, or about 10 percent of the total population. If the survey continues for a century, the total will rise to about 40 percent. Since the interval between such impacts is greater than 100 years, it is moderately likely that the survey will detect the "next Tunguska" event with ample warning for corrective action. However, in contrast to the ECAs and even the long-period comets, this survey will not achieve a near-complete survey of Earth-crossing objects in the 100-m size range in less than a several centuries with current technology. If there is a societal interest in protecting against impacts of this size, presumably advanced technologies will be developed to deal with them.

9.2 Survey Network: Cost and Schedule

The proposed Spaceguard Survey network consists of six telescopes of 2- to 3-meter aperture together with a central clearinghouse for coordination of the observing programs and computation of orbits. It also requires access to observing time on existing planetary radars and optical telescopes for follow-up. For purposes of this discussion, we assume that the Spaceguard Survey will be international in operations and funding, with the United States taking a leadership role through the Solar System Exploration Division of NASA's Office of Space Science and Applications.

9.2.1 The Spaceguard Survey Telescopes

The six survey telescopes required for the Spaceguard Survey are new instruments optimized for the discovery of faint asteroids and comets. While it is possible that one or more existing telescopes could be retrofit for this purpose, we expect that the most cost-effective approach is to design and construct telescopes specifically for this project. For purposes of this Report, we consider a nominal telescope design of 2.5 m aperture and 5.2 m focal length with a refractive prime-focus corrector providing a field-of-view of at least 2 degrees. The telescope will have altitude-azimuth mounting and be capable of pointing to an accuracy of a few arcsec and tracking to a precision of a fraction of an arcsec at rates up to 20 times sidereal. We assume that each telescope will be located at an existing observatory site of proven quality, so that no site surveys or new infrastructure development (roads, power, etc.) is required. The nominal aperture of 2.5 m is optimized for the ECA survey, but we note that larger telescope aperture (3 m or even more) would permit long-period comets to be detected at greater distances and thereby provide both greater completeness and months of additional warning.

An instrument of very similar design has recently been proposed by Princeton University for a wide-angle supernova survey. We believe that the SPACEGUARD Survey Telescopes could similarly be built for about $6 million each, including observatory building, but not including the focal plane of several mosaiked CCD detectors or the supporting data processing and computation capability. For each telescope, we allocate $1 million for the focal plane and $1 million for computer hardware and software, for a total cost per installation of $8 million. If these six telescopes were purchased together, the capital costs would thus be about $48 million.

For an estimate of operating costs, we assume that each telescope will require the following staffing: 2 astronomers, 2 administrative support personnel, 3 telescope operators, 1 each senior electronic and software engineers, and 2 maintenance and support technicians, for a total of 11 persons. Additional funds will be needed for transportation, power, sleeping accommodations for observers, and other routine costs associated with the operation of an observatory; the exact nature of these expenses depends on the location and management of the pre-existing site where the telescope is located. The total operations for each site should therefore run between $1.5 million and $2.0 million per year. In making this estimate we assume that each survey telescope is dedicated to the Spaceguard effort, and that it will be in use for about three weeks (100-150 hours) of actual observing per month. If it is intended that the telescope be used for other unrelated purposes when the Moon is bright, we assume that the other users will pay their prorata share of operation costs.

The Spaceguard Survey Operations Center should provide overall coordination of the international observing effort, including rapid communications among the survey telescopes and those involved in follow-up observations. The Spaceguard Survey Operations Center will also compute orbit ephemerides and provide an ongoing evaluation of the hazard posed by any object discovered by the Survey. Similar functions are performed today for the much smaller number of known asteroids by the Minor Planet Center in Cambridge, Massachusetts. Scaling from that operation, we estimate an initial cost of $2 million for computers and related equipment, and an annual operating cost of $2 million.

A third component of the Spaceguard Survey Program is follow-up, including radar and optical observations. As noted previously in this Report, it would be desirable to have one or more dedicated planetary radars and large-aperture optical telescopes (4-m class). However, we anticipate that a great deal of useful work could be done initially using existing planetary radars and optical facilities. Therefore, for purposes of this Report, we simply allocate a sum of $2 million per year for the support of radar and optical observing on these instruments.

9.2.2 Spaceguard Management and Cost-Sharing

The total estimated capital costs for the Spaceguard Survey are $50 million, with operating costs of $10-$15 million per year. We anticipate that these costs would be shared among several nations with advanced technical capability, with the maximum expenditure for the U.S. (or any other nation) of less than half the total amount. For purposes of U.S. budgeting, we assume that NASA will pay the cost of two telescopes ($16 million) and the Operations Center ($2 million), and will support operating costs of $5 million per year.

Management of the U.S. component of the Spaceguard Survey could be accomplished by NASA in one of two ways. (1) The telescopes could be constructed and operated by universities or other organizations with funding from NASA Headquarters through grants or contracts, as is done today with the NASA IRTF telescope on Mauna Kea (owned by NASA but managed by the University of Hawaii under a five-year contract) or the 0.9-m Spacewatch Telescope on Kitt Peak (owned and operated by the University of Arizona with partial grant support from NASA). (2) NASA could construct and operate the telescopes itself through one of its Centers (JPL or Ames, for example); the Centers might contract with universities or industry for operations but would retain a more direct management control. Similarly, the Spaceguard Survey Operations Center could be located at a NASA Center or could be supported by grants or contracts at a university or similar location, such as the present Minor Planet Center at the Harvard-Smithsonian Center for Astrophysics. In any case, international cooperation and coordination is essential, and an international focus is required from the beginning in planning and supporting this program.

9.2.3 Initial Steps

The construction of the new Spaceguard Survey telescopes will require approximately four years from the time funding is available. In the meantime, several steps are essential to ensure a smooth transition from the present small surveys to the new program. (1) An international coordination effort should be initiated by NASA, independent of but coordinated with the International Astronomical Union Working Group on Near Earth Objects, in order to plan for the orderly development of the Spaceguard Survey network. (2) The small cadre of current asteroid observers should be strengthened. Additional expenditures of about $1 million per year on existing teams would allow for expansion of personnel, purchase of badly needed new equipment, and greater sky coverage. Consequently, the discovery rate of ECAs should double to quadruple, thereby also increasing our confidence in modeling the population of such objects and planning the requirements for operation of the full-up survey. (3) In order to gain additional experience with the kind of automated CCD scanning techniques proposed for the Spaceguard Survey, efforts should be made as soon as possible to place in operation a telescope that utilizes these techniques; one such option is the proposed 1.8-m Spacewatch telescope at the University of Arizona. Efforts are also required in studying the use of CCD arrays and in developing appropriate software to support CCD scanning. (4) Continuing support should be provided for research on near-Earth asteroids and comets, including their dynamics and their physical properties. For purposes of this study, we assume an increase of $2 million/year beyond current NASA expenditures for these programs, to be maintained during the transition period.

9.2.4 Proposed Schedule for NASA Funding

On the assumption that the Spaceguard Program can begin in a modest way in FY93 and will reach full funding about FY95, we suggest the following possible schedule for new NASA support of this effort

TABLE 9.2: Proposed NASA Funding (in FY93 $M)

Fiscal Year	93	94	95	96	97	98	99	00
Transition	02	02	02	02	02	02	01	00
Capital Costs	01	02	04	04	04	04	00	00
Operations	00	00	00	01	02	02	05	05
Total	03	04	06	07	08	08	06	05

9.3 Conclusions

The Spaceguard Survey has been optimized for the discovery and tracking the larger ECAs, which constitute the greater part of the cosmic impact hazard. If any large ECAs threaten impact with the Earth, they could be discovered with ample lead-time to take corrective action. The Spaceguard system also will discover most incoming long-period comets, but the warning time may be only a few months. Finally, the great majority of the new objects discovered by the Spaceguard Survey will have diameters of less than 1 km; these should be picked up at a rate of about a thousand per month. It is therefore reasonably likely that even the "next Tunguska" projectile (20 megatons energy) will be found by the Spaceguard Survey if it is continued for several centuries

The Spaceguard Survey should be supported and operated on an international basis, with contributions from many nations. The total costs for this system are of the order of $50 million in capital equipment, primarily for the six survey telescopes, and $10-15 million per year in continuing operating support. However, these estimates will vary depending on the aperture and detailed design of each telescope, the nature of the international distribution of effort, and the management of the survey. In particular, larger telescopes would be appropriate if greater emphasis is to be given to the search for long period comets. Whatever the exact cost, however, the proposed system can provide, within one decade of its initial operation, a reduction in the risk of an unexpected large impact of about 50 percent at a relatively modest cost. Of course, additional and much greater expenditure would be required to deflect an incoming object if one should be discovered on an impact trajectory with the Earth, but in that unlikely event the cost and effort would surely be worth it. The first and essential step is that addressed by the Spaceguard Survey: to carry out a comprehensive survey of near-Earth space in order to assess the population of near-Earth asteroids and comets and to identify any potentially hazardous objects.

8.1 The Necessity of International Cooperation

That the hazard posed by NEO's is a problem for all humankind hardly needs repeating. The likelihood of a particular spot being the target of an impact is independent of its geographic position, so that we are all equally at risk. Further, each person on the face of the planet would be severely affected by a large impact, as discussed in Chapter 2.

The problem is thus international in scope; it is also international in solution. To obtain the spatial and temporal coverage of the sky that is required by the search program outlined in Chapter 7, a wide geographical coverage of optical observatory sites is essential. Even if these sites were limited to six, still at least five countries would likely be involved directly as telescope hosts. However, the number of nations actually involved would be larger than this. If Australia were one site then most likely the Anglo-Australian Observatory would be the organization acting as host, implying British involvement. Similarly a site in India, where a Spacewatch-type instrument is currently being developed, might involve a continuation of direct U.S. collaboration. Some of the best observatory sites in the southern hemisphere are in Chile, and if plans go ahead for the development of a large southern radar in Brazil, again the number of countries increases. The need for international cooperation is obvious, and rapid and efficient international communication through a central agency is a requirement.

Chapter 8: International Cooperation
8.1 | 8.2 | 8.3 | 8.4

8.2 Current International Efforts

The independent character of the scientific endeavor as well as

limited funding resources has resulted in a current program to find and track NEOs that is quite fragmentary. Generally it has been possible, in recent years, for discoveries made by one team to be followed up by other observers, but this has not always been the case, allowing some newly-discovered NEOs to be lost. For the program planned here this must not be allowed to occur, emphasizing the need for an international effort with close cooperation and priorities to be set by a central organization. The present level of our knowledge of NEO's has only been possible because of the services of the staff of the Central Bureau for Astronomical Telegrams and the Minor Planet Center (Cambridge, Massachussetts) who coordinate the analysis of observations of NEO's and make every effort to ensure that sufficient coverage occurs. A continuation of such a service on a larger scale will be necessary if the proposed program is to be brought to fruition.

There have in the past been some efforts made at formally organizing a search program on an international scale, quite apart from the informal links and communications made possible by personal contacts. The most prominent of these organizations has been INAS, the International Near-Earth Asteroid Survey, coordinated by E.F. Helin (Helin and Dunbar, 1984, 1990). INAS has resulted in increased cooperation between observatories in various countries, and hence an increase in the discovery rates. Apart from the U.S., scientists from the following countries have been involved in INAS: France, Italy, Denmark, Sweden, Bulgaria, Czechoslovakia, Yugoslavia, Germany, China, Japan, Russia, Ukraine, United Kingdom, Canada, Australia, and New Zealand.

The major thrust of INAS has been to coordinate the efforts of the large wide-field photographic instruments with regard to temporal and sky coverage. An immediate expansion of this effort can increase the current discovery rate, thus providing valuable information on the true statistical nature of the NEO population and associated impact hazards before the full network of survey telescopes becomes operational. Such a program will also serve as a training ground for new personnel and provide valuable experience with improved international communication and coordination.

A Spacewatch-type telescope is currently under development in India with the joint support of the U.S. Smithsonian Institution and the Government of India. Another international effort is being proposed by the Institute for Theoretical Astronomy in St. Petersberg, Russia, under the direction of A.G. Sokolsky. This group organized an international conference The Asteroid Hazard in October 1991, which endorsed the idea that NEOs "represent a potential hazard for all human civilization and create a real threat of regional catastrophes"

and noted "the necessity of coordinated international efforts on the problem of the asteroid hazard." This group has asked the Russian Academy of Science to support the formation of an International Institute on the Problem of the Asteroid Hazard under the of the International Center for Scientific Culture -- World Laboratory, and they propose to coordinate asteroid search and follow-up observations in central and eastern Europe.

8.3 Funding Arrangements

If this international survey program is to succeed, it must be arranged on an inter-governmental level. To ensure stability of operations, the NEO survey program needs to be run by international agreement, with reliable funding committed for the full duration of the program by each nation involved.

There are good reasons for the funding to be expected to be derived from all nations directly involved in the program. First, most countries usually want to provide for their own defense rather than to rely upon another or others to do this for them, so we may anticipate that nations in the world-wide community will wish to each play their own part in defending the planet. Second, although this program is large compared with present NEO search efforts, in fact it would be of quite a small overall budget. Thus it is possible for nations to make a significant contribution with little expense whereas it would not be possible for them to buy into a large space project, or even the construction of a ground-based 10-meter-class astronomical telescope. For example, there is a small group in Uruguay who study dynamical aspects of NEO's, and they could provide an essential service to the program; or the telescopes available for follow-up work in New Zealand or Romania could be utilized, and thus those nations gain prestige on the international scene at little expense. Involvement in space programs (which this program is, in essence) is generally viewed favorably by the populace of most countries. Third, this program may be a significant technology driver, so that money spent on the investigation and development of new technologies can be viewed as an investment rather than an expenditure.

With the encouragement of the United States as prime mover, the

funding for national sectors of the overall international search program should be attainable locally. For example, Australia and the United Kingdom, through their joint observatory in Australia, could immediately boost the current discovery rate to about 100 per year using existing equipment and technology given supplementary funding from those countries of the order of $0.25 million per year, although we would anticipate that this effort would be superseded by the introduction of CCD detectors within five years. Photographic searches currently being carried out in the United States might require a similar boost in funds, with a concomitant boost in discovery rate resulting, and the Spacewatch effort could also be significantly expanded by approval for the upgrade to 1.8-m aperture and funding to run the camera on more than eighteen nights per month.

8.4 International Sanction

The astronomical program outlined in this report already has the support of various international bodies. There is a burgeoning awareness in the astronomical community that the NEO impact hazard is a topic that requires attention for reasons other than altruistic scientific pursuit. At the 1991 General Assembly of the International Astronomical Union held August 1 in Buenos Aires, Argentina, the following resolution was passed:

> The XXIst General Assembly of the International Astronomical Union,
>
> Considering that various studies have shown that the Earth is subject to occasional impacts by minor bodies in the solar system, sometimes with catastrophic results, and
>
> Noting that there is well-founded evidence that only a very small fraction of NEO's (natural Near-Earth Objects: minor planets, comets and fragments thereof) has actually been discovered and have well-determined orbits,
>
> Affirms the importance of expanding and sustaining scientific programmes for the discovery, continued surveillance and in-depth physical and theoretical study of potentially hazardous objects, and

Resolves to establish an ad hoc Joint Working Group on NEOs, with the participation of Commissions 4, 7, 9, 15, 16, 20, 21 and 22, to:

1. Assess and quantify the potential threat, in close interaction with other specialists in these fields
2. Stimulate the pooling of all appropriate resources in support of relevant national and international programmes;
3. Act as an international focal point and contribute to the scientific evaluation; and
4. Report back to the XXIInd General Assembly of the IAU in 1994 for possible further action.

The Working Group, to be convened by A. Carusi of Italy, comprises the following scientists:

A. Bazilevski (USSR)
A. Carusi (Italy)
B. Gustafson (Sweden)
A. Harris (USA)
Y. Kozai (Japan)
G. Lelievre (France)
A. Levasseur-Regourd (France)
B. Marsden (USA)
D. Morrison (USA)
A. Milani (Italy)
K. Seidelman (USA)
G. Shoemaker (USA)
A. Sokolsky (USSR)
D. Steel (Australia/UK)
J. Stohl (Czechoslovakia)
Tong Fu (China)

This Working Group was selected not only on the basis of the geographical spread of persons active in the general area, but also in terms of expertise in distinct areas of the necessary program (e.g. celestial mechanics, generation of ephemerides, physical nature of NEO's, dynamics of same, relationship to smaller meteoroids and interplanetary dust). Five of these 16 individuals are also members of the NASA International NEO Detection workshop, ensuring appropriate continuity of effort.