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NEO scientific and policy developments, 1995–2000

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Abstract

Scientific and policy developments in the field of Near-Earth Objects (NEOs) since the UN NEO conference in 1995 are briefly outlined. Some areas of research and discovery have exhibited considerable progress while others have languished. In particular, facilities in the southern hemisphere for discovery and tracking of NEOs are inadequate. Suggestions are made both at the scientific and technical levels as well as at the policy level to provide coordinated and coherent progress in developing a long-term approach to NEO hazard mitigation. The next step should be the establishment of a panel of international scientific experts on the subject.

1. Introduction

In 1995, the UN Office for Outer Space Affairs hosted an international meeting on Near-Earth Objects (NEOs) at UN Headquarters in New York. At the conclusion of this meeting, a summary (Rapporteur's) report was prepared and within a year a related report was published in this journal [1]. It has been about six years since the UN meeting and about five years since the publication of the perspectives from that meeting. During this period, several NEO events have occurred on the scientific, technical and policy levels. This article will report on what we understand to be some of the most prominent of these developments in terms of their relationship to NEO policy issues within the context of the recommendations following the UN conference on NEOs. These recommendations suggested the establishment of adequate observational facilities and supporting technology, i.e. charge coupled devices (CCDs), vigorous space exploration of NEOs, research on NEO-like (surrogate) materials, improved astronautical capabilities, developing a better understanding of NEO orbital dynamics, and the need for long-term funding within the context of global political support. Much progress has occurred in many of these areas, while in others little headway has been made. In addition, many other supporting developments in science and technology have also taken place which, while scientifically and technologically worthwhile and supportive of NEO studies, cannot practically be accommodated within this brief article.

To assess succinctly NEO developments during the past five years, the summary presented here will be divided into two parts: scientific and technical developments and policy background issues. The former will be divided into five subsections: observations, orbital computations, satellite reconnaissance, material properties and astronautics. The latter will discuss important NEO reports—such as those contained within the UNISPACE III meeting in 1999 and the more recent UK Task Force Report in 2000—that have appeared since the 1995 UN Conference.

2. Part I: scientific and technical issues

2.1. NEO observations

The first and key step in avoiding a potential NEO hazard is a survey that leads to the discovery of NEOs by large field of view telescopes (FOV). Up until about 1995, most of the major telescopes involved in asteroid detection used photographic plates, the primary examples of which are the Palomar Observatory teams which used a 0.46 m Schmidt telescope with a limiting magnitude of about 17.5. Currently, to establish an effective NEO discovery program, a telescope with a large FOV and adequate focal plane instruments, such as fast read-out CCD, are required. The first facility to

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adopt electronic (CCD) instrumentation at the telescope focal plane for a regular NEO observation discovery program was Spacewatch at Kitt Peak, AZ. Since 1989, Spacewatch has had a 0.91 m Newtonian with a 2048×2048 pixel array CCD at the focus which provided a FOV field of view of about $0.5^\circ \times 0.5^\circ$. This was the primary NEO discovery facility in the Spring of 1995 and was capable of detecting an object with a magnitude of 20.5 or better (a significant improvement over 17.5), thus allowing the detection of fast moving close objects with small diameters. A 1.8 m telescope is expected to be fully commissioned by 2001, and is also now operational.

The next improvement in detection came about in December 1995, when the near-Earth asteroid tracking (NEAT) was initiated through the use of a 1.2 m (US Air Force) GEODSS telescope on Maui. The NEAT system used a 4096×4096 CCD array which provided a 2.5×2.5 square degree FOV. However, by December 1996, the NEAT program no longer had access to the original Maui site, and now uses the old AMOS facility on Maui. The 1.2 m Schmidt telescope at Mt Palomar has been upgraded to use the NEAT camera. NEAT does both survey and follow-up observations.

A major advance in NEO detection occurred when Lincoln near-Earth asteroid research (LINEAR) became initially active in March 1997 in New Mexico. Since 2000, LINEAR has been using two 1 m US Air Force telescopes attached to a 2560×1960 frame transfer CCD which allows signal readout to occur while a new image is being integrated. In its first extended month of operation (March 1998), LINEAR carried out 151 000 asteroid observations among which were the detection of 13 new NEOs. LINEAR is continuing to carry out many NEO observations and is (still) by far the premier NEO discovery facility, which provides a model for future NEO observation technology.

Since the UN conference in 1995, four additional discovery programs have come on line:

- the Lowell Near-Earth Object Survey (LONEOS) in Flagstaff, Arizona, which uses a 0.6 m Schmidt with a FOV of about 10 square degrees and a 4096×4096 CCD;
- the Observatoire de la Cote d'Azur (ODAS) which uses a large Schmidt (150/90 cm) with a field of view of about 0.3 square degrees and a 4096×4096 CCD; Since April 1999, this observing program has been discontinued;
- the Bejing Astronomical Observatory uses a Schmidt (90/60 cm) telescope with a FOV of about one square degree with a 2048×2048 CCD;
- the Catalina Sky Survey at Kitt Peak, AZ uses a 0.4 m Schmidt (46 cm) telescope with a FOV of 78.4 square degrees with a 4096×4096 CCD. This telescope was replaced by a 0.7 m telescope in late Autumn 2000, but as of the time of writing has yet to become operational.

Additional facilities that are coming on line include:

- the Japan Spaceguard Association (Bisei Spaceguard Center), which is currently using a 0.5 m telescope for NEO search and tracking space debris. It will be upgraded with a 1 m Cassegrain type F/3 telescope with a 3 square degree FOV with a 2000×4000 CCD, and is now nearing completion.
- the Klet observatory, Czech Republic, has 0.57 and 0.63 m CCD-based telescopes with an additional 1.02 m telescope being built. These telescopes are primarily tasked for follow-up work.

As can be seen from the above listings, all the major discovery facilities are in the northern hemisphere. This may present a problem in discovering some NEOs [2]. Currently, there are recommendations for a dedicated NEO discovery facility in the southern hemisphere [3], which have been supported by the "Government Response to the Report of the task Force on Potentially Hazardous Near Earth Objects [4]. It is hoped that such recommendations will be further acted upon. The spirit of this response encourages a momentum building towards the establishment of a premier facility in the southern hemisphere.

Discovery of an NEO, while very important, is only the beginning of the process of precisely characterizing its orbit. To determine adequately the NEO orbit, there is also a need for follow-up observations. Again, except for Siding Spring and a few amateur observers, the dearth of observing facilities in the southern hemisphere significantly limits the amount of follow-up observation work that can be carried out.

In addition to the above survey instruments whose goal is the discovery of NEOs, there are also the astrometry and gross structure measuring radar instruments at Arecibo, Puerto Rico (300 m antenna) and Goldstone, California (70 m antenna) which have been active over the past decades. No new radar facilities have been brought on line in the USA since then, although more recently the DLR Planetary Radar, in Weilheim, Upper Bavaria, has a 30 m antenna and also uses radar transmitters in Ukraine (Crimea) and USA.

The NEO search, discovery and follow-up facilities in the northern hemisphere may be adequate for larger objects ($\gtrsim 1$ km) but, not for detailed physical characterization. However, there is a need for at least one additional discovery facility and a few follow-up facilities in the southern hemisphere.

2.2. *Computation of orbits*

The computation of many NEO orbits can be quite complicated and involves in some cases chaotic orbit analysis, depending on the time scale involved. This is one reason why long-term prediction of impact probability is quite difficult. For example, after each orbital period, the suite of gravitational interactions of an NEO is very likely to change. In addition, to a greater or smaller extent, some NEOs (comets) can be subjected to non-gravitational forces. Furthermore, a single night's discovery data is not adequate to determine a NEO orbit. Several additional nights of follow-up observations are generally required as discussed in the previous section. Going beyond that, supplementary assistance can be provided by archival data, such as old photographic plates, when available. However, with the enhanced rate of discovery since LINEAR has come on line, the computational burden on the Minor Planet Center in Cambridge has increased markedly. Fortunately, thanks to some timely funding and a staff increase they have been able to continually provide accurate and reliable computations and disseminate such promptly. Long term support for the institution is absolutely necessary to maintain a continuous stream of organized observational data and accurate orbital computations that can be provided in a timely manner.

Because an NEO is continually interacting with a potentially changing group of different objects, NEO impact probability is a secular parameter which limits long-term prediction, and therefore the so-called impact probability. This leads to another problem in terms of the public's perception of the meaning of the NEO hazard as expressed by an impact probability. The case of 1997 XF 11 is a good example where the orbital computations, based on the currently available data, correctly indicated a small probability of Earth impact [5]. In this case, with additional data provided by old plates and supported by subsequent follow-up observations, the same computation indicated that an impact would not occur and that the NEO did not pose an immediate threat (for millennia, it is thought). However, it cannot be assumed that the public at large will be likely to understand such refinements in orbital computation (and their secular variations) and, therefore, upon being exposed to some information regarding a possible NEO impact, they may become alarmed. In this sense, the results of orbital computations, such as the very misleading term 'NEO probability of impact' can effectively become a social policy issue.

Orbital analysis and computations is an area where a small amount of funding can provide a large scientific payoff in terms of understanding the effects of orbital resonances and non-linear trajectories. In addition to providing the critical benefit of reliable trajectories for hazard mitigation, if necessary, an accurate and reliable understanding of orbital trajectories would also have an immediate benefit in that potential threat levels can be realistically assessed and impact probabilities could be better communicated to political leaders, as well as to the public.

2.3. Satellite reconnaissance

Since satellite reconnaissance can provide invaluable data on the NEO material properties, it is a key element both in understanding the origin and evolution of asteroids and comets and in mitigating the potential NEO hazard because unless details are understood about the material properties of these objects, any mitigation effort will work at a severe disadvantage. Fortunately, a tradition of satellite based space reconnaissance is well established. Before 1995, there were several NEO related space-based missions which included:

- The International Cometary Explorer (ICE), launched in 1978, which passed through the tail of comet 21P/Giacbini–Zinner in 1985 and carried out a distant flyby of comet 1P/Halley in 1986;
- Vega-1 and 2 (Russian) which carried out close approaches to comet Halley in 1986;
- Giotto which also made a close approach to comet Halley in 1986;
- Sakigake and Suisei, which carried out a flyby of comet Halley to observe interactions with solar wind in 1986;
- Galileo, which carried out a flyby of asteroids Gaspra in 1991, and Ida in 1993, observed comet Shoemaker–Levy 9's impact on Jupiter in 1994, and made a rendezvous with Jupiter and its moons in 1995.

Between 1995 and 2000, three space-based NASA missions were launched:

- Near-Earth Asteroid Rendezvous (NEAR), which carried out flybys of Mathilde in 1997, Eros in 1999, an Eros rendezvous in 2000 and the dramatic descent onto the surface of Eros in February 2001 and which unequivocally demonstrated what can be accomplished through excellent spacecraft design and orbital execution.
- Deep Space 1, which carried out flybys of asteroid Braille in 1999 and comet 19P/Borrelly in 2001.
- Stardust, launched in 1999, is anticipated to probe within 100 km of comet 81P/Wild 2's nucleus in 2004 and carry out a sample return in 2006.

Several missions are expected to be launched in the next few years, including:

- Comet Nucleus Tour (CONTOUR) flybys of comets 2P/Encke in 2003, 73P/Schwassmann-Wachmann 3 in 2006, and 6P/d'Arrest in 2008;
- MUSES-C, which will rendezvous with asteroid 1998 SF36 in 2005;
- The Near-Earth Asteroid Prospector (NEAP), a non-governmental deep space mission to asteroid 4660-Nereus, with a possible launch in 2001;

- A ROSETTA flyby of asteroids 4979-Otawara in 2006 and 140-Siwa in 2008, and rendezvous with comet 46P/Wirtanen in 2011;
- Deep Impact comet 9P/Tempel 1 collision encounter in 2005;
- Pluto–Kuiper Express encounter with Pluto in 2012–2020 and then passing through other members of the Edgeworth–Kuiper belt of comets;
- Deep Space 4 (possible) lander on an active comet nucleus with possible sample return to Earth.

The space agencies NASA and ESA should be commended for their vigorous efforts to gain new knowledge of the asteroid and comet material properties and provide a de facto basis for governmental commitment to NEO studies. Indeed, NASA's stated goal for 90 percent of the near-Earth asteroids (NEAs) larger than 1 km to be found by 2009 is a clear-cut commitment to dealing with the NEO problem at the observational level. It is estimated that there are 900 objects larger than 1 km, about half of which are said to have been discovered. However, those NEAs which have already been discovered are those which were generally most easily detectable; the remaining objects may have orbits which make their detection more difficult. In addition, smaller NEAs (~ 200 m) and rapidly moving comets at high inclination angles also pose a substantial threat and somewhere along the line must be dealt with in a serious manner. It will require a major international effort just to discover smaller threatening NEOs, to implement a follow-up program to provide recovery, and to assess their threat in terms of the probability that one of these objects will approach Earth to within a given distance. Discovery without follow-up will minimize the value of the discovery. Therefore, such efforts should continue and even be enhanced, during the next few decades, and joined together with those of other nations that can also contribute to this very important discovery and exploration.

2.4. Material properties

Closely related to the interpretation of the satellite reconnaissance programs is the study of NEO material properties. A good example of satellite reconnaissance supporting material science studies and related astronautical missions is the recent NEAR mission to both Mathilde and Eros which provided direct information regarding the diversity of asteroid bodies. This diversity in the asteroid population [6] should always be borne in mind because a knowledge of the range of material properties of NEOs is important not only for understanding their origin and evolution, but also for optimizing the success of any mitigation effort [7]. Because of the enormous energy that could be involved in a NEO mitigation effort (up to petajoules) high density energy sources would most likely be used. Such interactions can be quite complicated because of the response of the different NEO materials in different physical states to various forms of high energy density impulses. Therefore, it is important to study the effects of the interaction of high energy density photons and neutrons on NEO surrogate materials in order to determine momentum coupling [8]. Experimental work in this area has been initiated, to a limited extent. This is an area in which additional experiments must be carried out.

2.5. Astronautics

While the current satellite reconnaissance missions are adequate in terms of learning about the minor bodies of the solar system, they are limited in their astronautical capabilities because they are dependent upon certain launch windows and gravitational interactions with planetary bodies. For this reason, launches capable of reaching only a small population of potential targets must be planned long in advance and only at specific times (gravitational windows). However, if a NEO is found to be potentially threatening, a potential interactive reconnaissance and/or mitigation mission may be required at any time at any target coordinate. Current satellite mission capabilities are not generally suited to this task. To bring attention to this issue, my earlier paper on NEOs argued for research and development on long range (1 AU) hybrid rocket technologies with continuous (long-term) acceleration periods adequate to reach a threatening NEO in an operationally realistic time scale [1]. Except for the development of ion (plasma) propulsion systems little research and development has been done in this area. Ideally, so-called type-II rockets with large specific impulses should be available for a reconnaissance or mitigation rendezvous. It is understood that the development of such rocket technology would be quite expensive and might necessitate the collaboration of several countries.

3. Part II policy issues: UNISPACE III and the Vienna declaration

Policy perspectives emerged from the 1995 UN NEO Conference to increase awareness of the threat from NEOs and to provide guidelines for cooperative observation, research and mitigation programs. These policy perspectives included:

(a) Initiation of discussions on the extension of the guidelines of Articles V and XI of the 1967 Outer Space Treaty to include NEOs.
(b) Provision of an international mechanism for sharing information on NEOs considered to be a potential

threat. A first step towards this objective has been initiated by the IAU, which has created a working group on NEOs. The Smithsonian Astrophysical Observatory in Cambridge, MA is the IAU clearing house for asteroids and comet discoveries and supports those activities by rapidly disseminating astronomical observations and providing accurate and reliable orbital data.

(c) Establishing a ground-based observation network, with the participation of developing nations, which will also serve as a network of facilities for the introduction to observational science. Observations can be coordinated with professional observatories to provide follow-up observations when appropriate.
(d) Organizing international exploration teams to investigate prominent impact craters on Earth.
(e) Exploration of the concepts of NEO planetary defense within the framework of the existing guidelines of international law and the 30-year-old nuclear Non-Proliferation Treaty with a view to NEO mitigation scenarios.
(f) Establishing an international and interdisciplinary committee consisting of states parties to the treaty under UN auspices (items a and b above) to provide guidelines for classifying NEO threats under the guidelines of Article V, which deals with hazards to astronauts in particular and can be extended to people in general.

Since the 1995 conference, a number of meetings have been conducted with internationally recognized perspectives on policy making with regard to NEOs. UN member states, which participated in the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space (UNISPACE III), held in Vienna from 19 to 30 July 1999, took note with satisfaction of the valuable contributions of participants of the Technical Forum and the Space Generation Forum to the work of UNISPACE III. The Vienna Declaration on Space and Human Development, which was formulated during the conference, declared, inter alia, that the following items serve as the nucleus of a strategy to address NEO challenges in the future:

Towards advancing scientific knowledge of space and protecting the space environment, action should be taken to:

(a) improve the scientific knowledge of near and outer space by promoting cooperative activities in such areas as astronomy, space biology and medicine, space physics, the study of NEOs and planetary exploration;
(b) improve the protection of the near-Earth space and outer space environments further research in and implementation of mitigation measures for space debris should be carried out;
(c) improve the international coordination of activities related to NEOs, harmonizing the worldwide efforts directed at identification, follow-up observation and orbit prediction, while at the same time giving consideration to developing a common strategy that would include future activities related to NEOs, should be implemented.
(d) protect the near and outer space environments through further research on designs, safety measures and procedures associated with the use of nuclear power sources in outer space [9].

UNISPACE III, through the Technical Forum, highlighted NEOs as objects of scientific inquiry, raising major issues, among them the inadequacy of current knowledge, confirmation of hazard after initial detection, disaster management, methods of mitigation including deflection, and reliable communication with the public.

Another significant policy development milestone occurred in January 2000, when the British National Space Centre announced the establishment of a government task force to investigate the threat posed to the Earth by asteroids and comets and how the UK should contribute to an international effort on NEOs. The *Report of the Task Force on Potentially Hazardous NEOs* made the point that the effort of assessing the impact hazard by charting and studying the population of potential impactors has to be international and may involve both ground-based and space-borne studies. A number of the concluding, specific recommendations refer to the UN and the International Astronomical Union as international organizations that may take the lead to endorse a world-wide plan for NEO observation and follow-ups, thus emphasizing the global nature of the threat. However, the Report of the Task Force also noted that no UN body or agency can at present be held to represent the global interest in protection from NEOs. It was thought that the UN Committee on the Peaceful Uses of Outer Space is too narrowly focused and UNESCO, with its brief on science in general, is too wide. A solution to this may be anticipated along the lines of the (UN) Intergovernmental Panel on Climate Change with its three main working groups on science; on the impacts of change; and on how such change might be mitigated. A similar Intergovernmental Panel on Threats from Space, established and financed by participating UN Member States, would provide a mechanism for coordination and consultation, issuing periodical assessments as the situation requires. Regarding intergovernmental aspects, the Inter-Agency Debris Coordination group (covering the space agencies of the USA, Russia, China, India, Japan, Ukraine and Europe) might be able to contribute; and, for certain aspects, so might the UN Committee on the Peaceful Uses of Outer Space.

4. Conclusions

Developments during the past five years have seen some significant technical progress in NEO studies in some areas and little movement in others. Specifically, in the area of satellite reconnaissance missions there has been a considerable de facto commitment to NEO studies by NASA and ESA, as dramatically exemplified by the NASA/NEAR mission and generally supported by NASA's NEA discovery goals. International commitment coming to grips with a potential NEO hazard is underscored by the (UK) government response to the *Report of the Task Force on Potentially Hazardous NEOs*, which represents outright support and explicit action items for an international approach to NEO studies, as outlined in 14 specific recommendations [4]. Furthermore, the support for the LINEAR telescope, which dominates the discovery statistics, to specifically search for NEOs represents another important (US) government operational commitment to NEO studies which can serve as a model for future observational work. However, these observational successes must be extended even further, and other areas of research which have not yet received much direct support should receive the assistance that they deserve. As a means of dealing with the NEO threat, it is therefore suggested that in order to construct a coherent and coordinated assessment of the potential NEO hazard and to establish the scientific and technological requirements to carry out this objective, an international panel of experts should be assembled and coordinated under the leadership of a distinguished international scientific panel. In this way, scientific experts can serve the international community [10]. Each of the of the five critical scientific and technical areas discussed above—observations, orbital computations, satellite reconnaissance, material properties and astronautics—should have their own subcommittees and chairs. These subcommittees can meet independently and communicate, both directly as well through a governing panel, to report their findings. Clearly, such an ensemble of committees could at least provide an intellectual framework to accommodate many new ideas, results of observations and experiments, locations for new telescopes, mission designs and related technologies, thereby furnishing a forum through which these new ideas could be critically examined and new facilities be implemented. The reports of this panel would be made available to governments to assist in the assessment of the potential NEO hazard. Because a potential NEO impact knows no geographical boundaries, it is truly an international problem. Therefore, the participants of the panel should be drawn from the international community, with guidance coming from the leading spacefaring nations, and with other nations supporting technically as well as financially. In this sense, participation means true commitment.

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References

[1] Remo JL. Policy perspectives from the UN international conference on near-earth objects. Space Policy 1996;12:13–7.

[2] Remo JL, Spahr T, Williams GV, Marsden BG. The geographical representation of big and small near-Earth asteroid (NEA) discoveries and observations, 2001, in preparation,

[3] British National Space Centre. Report of the Task Force on Potentially Hazardous Near Earth Objects. London, 2000, p. 56.

[4] Government response to the report of the task force on potentially hazardous near Earth objects. Crown Copyright: //www.dti.gov.uk/DTI/Pub/02/01/NP, 24 February 2001.

[5] Marsden BG. A discourse on 1997 XF11. Journal of British Interplanetary Society 1999;195–202.

[6] Gehrels T, editor. Hazards due to comets and asteroids. Tucson: University of Arizona Press, 1994.

[7] Remo JL. Classifying and modeling NEO material properties and interactions. In: Gehrels T, editor. Hazards due to comets and asteroids. University of Arizona Press: Tucson, 1994. p. 551–96.

[8] Remo JL. Energy requirements, payload masses for near-Earth objects hazard mitigation. Acta Astranautica 1999;47:35–50.

[9] United Nations. Report on the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space. United Nations Document A/CONF.184/6, New York, 1999.

[10] Dresden M, Kramers HA. Between tradition and revolution. In: Obligation and duty, vol. 4, 1987. p. 501–5. (chapter 18).