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Report
of the
NASA Advisory Council
Ad Hoc Task Force on Planetary Defense

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Executive Summary

The Ad-Hoc Task Force on Planetary Defense of the NASA Advisory Council was established on 15 April 2010 in order to advise the Council Chairman, the NASA Administrator, and NASA Mission Directorates on future agency actions related to Near-Earth Object (NEO) impact mitigation, known as Planetary Defense. Building upon previous, substantive work done by others to address the challenges of preventing a future NEO impact on Earth, the Task Force spoke to experts in the field and sought evidence from primary sources to inform its deliberations. The Task Force proposes five recommendations to the Council that suggest how NASA should organize, acquire, investigate, prepare, and lead national and international efforts in Planetary Defense.

Recommendation 1: Organize for Effective Action on Planetary Defense
NASA should establish an organizational element to focus on the issues, activities and budget necessary for effective Planetary Defense planning; to acquire the required capabilities, to include development of identification and mitigation processes and technologies; and to prepare for leadership of the U.S. and international responses to the impact hazard.

Recommendation 2: Acquire Essential Search, Track, and Warning Capabilities.
NASA should significantly improve the nation's discovery and tracking capabilities for early detection of potential NEO impactors, and for tracking them with the precision required for high confidence in potential impact assessments.

Recommendation 3: Investigate the Nature of the Impact Threat.
To guide development of effective impact mitigation techniques, NASA must acquire a better understanding of NEO characteristics by using existing and new science and exploration research capabilities, including ground-based observations, impact experiments, computer simulations, and *in situ* asteroid investigation.

Recommendation 4: Prepare to Respond to Impact Threats.
To prepare an adequate response to the range of potential impact scenarios, NASA should conduct a focused range of activities, from in-space testing of innovative NEO deflection technologies to providing assistance to those agencies responsible for civil defense and disaster response measures.

Recommendation 5: Lead U.S. Planetary Defense Efforts in National and International Forums.
NASA should provide leadership for the U.S. government to address Planetary Defense issues in interagency, public education, media, and international forums, including conduct of necessary impact research, informing the public of impact threats, working toward an internationally coordinated response, and understanding the societal effects of a potential NEO impact.

Introduction

For more than a decade, NASA has been searching for near-Earth objects (NEOs) that may pose a potential impact threat to Earth. Both the legislative and executive branches are considering what role NASA may play in expanding its NEO search and developing the capability to prevent or mitigate a future impact. The space agency has broad expertise in scientific exploration and characterization of near-Earth asteroids (NEAs) and comets (NECs), and NASA's deep space operations experience could enable the development of deflection technologies to be used to divert a NEO threatening an impact.

The Ad-Hoc Task Force on Planetary Defense of the NASA Advisory Council (hereinafter, "Task Force") was established on 15 April 2010 in order to advise the Council Chairman, the NASA Administrator, and NASA Mission Directorates on future agency actions related to NEO impact mitigation, or Planetary Defense (see Task Force Terms of Reference in Appendix).

The Task Force anticipates that the executive branch, in its current consideration of appropriate agency roles regarding the NEO impact hazard, will assign NASA a lead role for the U.S. government's activities for Planetary Defense. The recommendations herein reflect this assumption. If NASA is not assigned the leadership role for Planetary Defense, certain Task Force recommendations will apply instead to the responsible federal agency.

The Task Force recognizes that other entities have conducted substantial work addressing Planetary Defense challenges. The Task Force relied on this, other primary sources, and new information developed during its deliberations to inform its recommendations. In citing this work, the Task Force has minimized, for brevity, the repetition of supporting material for its recommendations. This material can be found in the References section.

Synergies from Planetary Defense

Near-Earth objects figure prominently in NASA's science exploration efforts via future robotic missions, in its search programs to detect a potential impactor, and now in its human exploration plans. Congressional direction in the George E. Brown Survey NEO Survey Act of 2005 (Section 321 of Public Law No. 109-155) regarding a survey of the NEO population, and current Office of Science and Technology Policy consideration of government responsibility for Planetary Defense, indicate that NEO activities will be part of NASA's exploration and technology efforts.

NASA's NEO research is a "three-dimensional" activity that advances our knowledge in solar system science, human exploration, and Planetary Defense. For a relatively small incremental investment in instrumentation or capability on science or exploration spacecraft, NEO missions designed for one goal can return substantial information useful to NASA's Planetary Defense activities.

For example, Planetary Defense mission goals (e.g. precision orbit determination; measurements of mass, density, porosity, and rotation state; investigation of the momentum multiplier; searching for NEO satellites, etc.) would also fulfill many fundamental scientific and human exploration objectives. In turn, robotic science spacecraft can demonstrate the precise proximity operations and guidance algorithms necessary for precision "slow push" deflection techniques. In preparation for visits by human explorers, investigation of a NEO's interior structure, physical properties, and stability of surface materials will furnish data useful for other deflection techniques, such as kinetic impact and regolith ablation.

Time is a fourth dimension for NEO research. Early integration of Planetary Defense objectives into NASA's research and exploration missions provides a cost-effective means to increase the maturity of our technology to meet future impact threats and eliminate duplicate flight missions.

Overall, the integration of Planetary Defense investigations into scientific and human exploration missions increases the return from any of NASA's NEO missions, meeting the needs of managers, policy makers, the science community and the public.

Findings on Planetary Defense

1. NASA's search for near-Earth objects has discovered at least 87% of the large asteroids whose impacts could pose a global threat to our civilization. None pose a credible threat of a collision with Earth for the foreseeable future. But the discovery rate of the much more numerous smaller NEOs, representing a regional or local impact hazard, will soon confront us with objects presenting worrisome but uncertain probabilities for a future collision with Earth. Such situations will appear more frequently as the discovery rate increases, and the nation presently has no clear policy on how to address such a situation.

2. The National Research Council's (NRC) 2010 report, "Defending Planet Earth," presents a thorough collection of background information describing the hazard of NEO impacts and NASA's current search, impact analysis, and warning programs. The NRC report authors examined several search options for detecting asteroids down to the 140-meter-size target specified by the George E. Brown NEO Survey legislation. The Task Force recommendations are largely based on the conclusions of the NRC report.

3. However, the NRC report authors had very limited time to examine emerging capabilities to discover, track, and provide warning for near-term impact of the smallest objects with damage potential (ten to several tens of meters in size). The Task Force supplemented the NRC's work to recognize that short-term warning could enable effective evacuation of affected areas.

4. This discussion of near-Earth objects encompasses active near-Earth comets (NECs) as well as near-Earth asteroids (NEAs). Both short- and long-period NECs comprise ~1 percent of the NEO population. The population of long-period comets, with orbits originating in the outer solar system, represents a small part of the total comet threat, and thus an even smaller part of the total impact hazard. Because the tasks of effectively detecting and deflecting objects of this size and velocity are beyond our present technology, the Task Force report does not address long-period comets.

5. The driving philosophy behind the national and international defense against NEOs should be, "Find them early." Early detection of NEOs (especially those larger than 140 meters in size) is key to mounting an effective--and *cost*-effective--Planetary Defense effort. An adequate search, detection, and tracking capability could find hazardous objects several years or decades before they threaten impact. Early detection and follow-up tracking of hazardous NEOs eliminates any need for a standing defense capability by mission-ready deflection spacecraft with their high attendant costs.

6. Accurate orbital predictions based on an adequate and credible search and tracking capability will eliminate many ambiguous impact threats from NEOs, ruling out a collision long before an expensive deflection solution becomes necessary. This requires reducing the uncertainty in any NEO's observed and predicted position. The Task Force refers to this strategy as "reducing the error ellipse" as rapidly as possible.

7. A relatively low-cost, early investment in search, track, and follow-up observations through ground- and space-based systems (including radar) is a powerful cost-saving strategy. Such a capability will pay off handsomely by enabling more accurate orbit determination; eliminating many predictions of NEOs with a worrisome probability of impact (an uncomfortably high, but uncertain, probability of Earth collision); and avoiding the launch of a deflection or even a transponder tracking spacecraft, each costing hundreds of millions of dollars.

8. To achieve the NEO search goals in a timely manner as directed by the 2005 George E. Brown NEO Survey legislation, the nation will likely require acquisition and operation of a space-based survey element in addition to ground-based systems. A spacecraft operating with sensors in the infrared band from an orbit sunward of Earth's (e.g., a Venus-like orbit) offers great advantages in rapid search and repeat observation frequency.

9. When used in conjunction with ground-based optical observations, radar data can dramatically improve orbit knowledge of recently discovered NEOs. However, radars have limited sky coverage and can observe NEOs only at relatively close range. A modest-aperture, space-based infrared telescope with its advantageous orbital geometry (an observing location and direction different than Earth's) could enable a much larger total of positional observations over much longer orbital tracks. Such tracking from

multiple solar system vantage points (e.g. Earth and a Venus-like orbit) will aid in quickly reducing orbit uncertainties when radar follow-up is unavailable.

10. While the search for the NEO population larger than 140 meters is underway and the necessary orbit precision is being obtained, there will be a transition period or window of perceived vulnerability, lasting at least two decades. Some NEOs will present worrisome probabilities of impact, and sufficient orbit precision to rule out an impact may not be obtained before a decision must be made to launch a deflection campaign. The more rapid search enabled by a space-based system will, by aiding early ground-based follow-up, shorten this window of vulnerability by several years. Impact threats will still appear as the catalog nears completion, but continuing observations will reduce uncertainty and increase warning time.
11. Physical characteristics of NEOs pertinent to Planetary Defense include size, mass, density, porosity, composition, rotation, interior structure, binary nature, and the properties of the surface. Our present knowledge is insufficient to understand the typical range of characteristics for NEOs comprising the potentially hazardous population. This knowledge base is essential for the most effective development and application of deflection measures. Simple physical characterization is also essential for accurate forecasting of impact effects for an object escaping deflection.
12. The Task Force strongly recommends that the cost of NASA Planetary Defense activities be explicitly budgeted by the administration and funded by the Congress as a separate agency budget line, not diverted from existing NASA science, exploration, or other mission budgets.

Planetary Defense Recommendations and Discussion

In response to the terms of reference established by the NASA Administrator, the Task Force makes the following recommendations, accompanied by supporting rationale.

Recommendation 1: Organize for Effective Action on Planetary Defense

NASA should establish an organizational element to focus on the issues, activities and budget necessary for effective Planetary Defense planning; to acquire the required capabilities, to include development of identification and mitigation processes and technologies; and to prepare for leadership of the U.S. and international responses to the impact hazard.

Task Force findings (anticipating the release by the OSTP of recommendations pursuant to Public Law 110-422) indicate that a focal point within the NASA Headquarters staff should be established to plan, coordinate, and oversee implementation of Planetary Defense (PD) related activities.

1.1. Planetary Defense Coordination Office (PDCO). NASA should name an officer, responsible directly to the NASA Administrator, to coordinate the necessary expertise and internal resources to establish a credible capability to detect any NEO impact threat, as well as plan and test measures adequate to mitigate such a threat. The PDCO officer should have the authority to:

1) Plan and submit budget inputs for a distinct and comprehensive Planetary Defense Program of related research, development, and implementation projects and activities.
2) Disburse approved budgets to appropriate mission directorates and directly to selected projects for implementation of incremental PD activities and capabilities.
3) Coordinate and oversee all activities by mission directorates, centers, and agency projects for PD related capabilities.
4) Plan, coordinate, and implement agency interfaces with other U.S. government agencies and departments for PD-related activities, as well as lead agency interaction with other space agencies and international partners. The PDCO should represent NASA in all interagency and international venues when PD-related issues are discussed.
5) Plan, coordinate, and implement all PD-related public awareness activities and campaigns. Implement procedures to approve any agency public information release related to any NEO impact threat or agency activities to mitigate such a threat. (See Recommendation 5.)

The PDCO should be assigned a small staff to accomplish the duties above, and assisted by personnel matrixed from the appropriate agency mission support offices.

1.2. PD Activities. The PD program plan should include a near-term effort to accomplish the George E. Brown NEO Survey goal in a reasonable period of time. This act directs NASA to detect, track, catalog, and characterize the typical physical attributes of at least 90 percent of NEOs with sizes of 140 meters or larger.

The PDCO should plan and budget for the incremental costs of maintaining the planetary radar tracking and characterization capabilities at the National Science Foundation's Arecibo and NASA's own Goldstone facilities, in addition to the space-based element noted in Finding 7. Support should continue through those facilities' planned life cycles, including any programmed upgrades to their capabilities.

Radar observations, when used in conjunction with optical observations of new NEO discoveries, are more effective than optical means at significantly improving knowledge of an object's orbit and reducing prediction uncertainties. In turn, increased orbit precision and reduction of the error ellipse in a NEO's predicted position reduces the likelihood of a worrisome probability of impact situation, and subsequent need for taking mitigation actions before a sufficiently precise miss distance or impact location is determined. If radar eliminates just one of these worrisome situations, it would more than offset its long-term operations costs.

1.3. Planetary Defense Budget. In the out years, the PDCO should plan and budget for long-term, continuous monitoring of the NEO population, beyond the interval required for reaching the near-term discovery goals. NEO orbits evolve over time, both episodically (due to gravitational encounters) and gradually (due to non-gravitational perturbations) and the NEO database will require periodic updates following the initial, intensive search and discovery period. New arrivals joining the NEO population from the main belt will also require discovery and cataloging. Once the catalog is substantially complete, existing ground-based elements will likely be sufficient for such follow-on monitoring.

Therefore, Planetary Defense funding requirements for detection, early warning, and mitigation/deflection demonstrations are substantially front-loaded. The Task Force finds that the Planetary Defense program plan is likely to require an annual budget of approximately $250 million to $300 million per year during the next decade to meet the mandated 140-meter search goal; execute selected NEO characterization missions; develop and demonstrate NEO deflection capabilities; and develop the analytic and simulation capacity necessary for NASA's PD role.

Once the search for potentially hazardous objects is substantially complete, the task shifts to ongoing monitoring and catalog maintenance. After flight demonstrations of the primary deflection concepts are completed, further experiments would be integrated into scientific or exploration missions. The PD program budget could then recede to operations and maintenance levels (approximately $50 million to $75 million annually).

1.4. Interfaces. A comprehensive PD plan must include development of important interfaces internal and external to the U.S. government. The PDCO should take immediate action to develop short-term impact warning procedures in conjunction with the DHS and other emergency response and consequence management agencies. This quick-response information interface should be designed in close coordination with the established disaster response community.

The PDCO should seek bilateral and/or multilateral international cooperative opportunities for NASA to initiate joint NEO deflection development/demonstration missions. An actual impact threat response will require international coordination, and deflection development can explore the capabilities, limitations, and trust necessary for such cooperation. Given the global nature of the hazard and the need for a coordinated response from the space-faring nations, it is both desirable and cost-effective for the US to seek international partners in demonstrating deflection capability.

The PDCO should lead NASA efforts, in cooperation with Department of State and other agencies as appropriate, to proactively challenge the international community to join in the analytical, operational, and decision-making aspects of Planetary Defense. Substantial efforts have been underway for over five years in the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS) and other space-related forums, to encourage international participation in NEO detection efforts. Current efforts to develop a standing NEO threat decision-making process--enabling the international community to effectively respond to an impact threat--could benefit substantially from U.S. and NASA leadership.

Recommendation 2: Acquire Essential Search, Track, and Warning Capabilities.

NASA should significantly improve the nation's discovery and tracking capabilities for early detection of potential NEO impactors, and for tracking them with the precision required for high confidence in potential impact assessments.

Our ability to project a NEO's orbit years into the future is accompanied by considerable uncertainty. The object's orbital plane will generally be known to good accuracy, such that the intersection of that plane with the orbit of the Earth can be predicted to within a relatively few kilometers. However, except in the case of a NEO observed on its terminal impact trajectory, a threatening NEO's exact orbital period will generally not be known accurately enough to predict whether an impact many years in the future will actually occur.

Decision-makers will thus frequently face the question of how to react to a NEO with a worrisome (but uncertain) probability of impact. For example, a particular NEO may have a 2 percent chance of impacting Earth on a particular day decades in the future. Waiting until ground-based observations improve the impact prediction to, say, 50 percent confidence will make an attempted deflection far more costly, if not physically impossible. Even the prompt launch of a robotic transponder mission to improve our knowledge of the NEO's orbit will cost several hundred million dollars for each potential impact threat.

Decisions of this sort will be very unpleasant for policy-makers. The Task Force recommendations seek to minimize these situations through development and deployment of search and tracking assets that reduce the uncertainty in a NEO's position, and thus the uncertainty in its impact probability. Reducing the number of such "worrisome probability of impact" situations via better NEO search and track technologies (producing observations that prove the more likely case that the asteroid will miss Earth) will be far less expensive than launching transponder missions or an actual deflection campaign. Parallel efforts to demonstrate cost-effective deflection technologies would help deal with those few objects with impact probabilities that remain too worrisome to ignore. The Task Force recommends that NASA choose search and deflection capabilities that minimize the total combined cost of confronting future impact threats.

2.1. NEO Search: To implement this recommendation, the Task Force recommends that NASA immediately initiate a space-based infrared telescopic NEO search project as the primary means of meeting the congressionally mandated George E. Brown NEO Survey goal.

NASA was tasked to discover 90 percent of the NEOs larger than 140 meters by the end of 2020 as part of the NASA Authorization Act of 2005 (Public Law No. 109-155). Both ground- and space-based options for meeting the George E. Brown, Jr. NEO Survey goals have been investigated. Although NASA should continue to assist state-of -the-art ground-based optical surveys, including those coming on line or planned by other agencies (e.g., PanSTARRS, LSST), one or more space-based infrared (IR) telescopes in an orbit interior to Earth's (e.g., a Venus-like orbit) offers several search efficiency advantages. Compared with ground-based optical systems, such space-based systems possess greater discovery efficiency and can more accurately determine the sizes and orbits of potentially threatening objects. The cost of such a survey asset is comparable to the multiple dedicated ground-based alternatives required, and will rapidly meet the legislated completion goal (probably within seven years).

Additionally, a space-based survey, with its advantageous observing geometry and frequency, will enable prompt and precise orbit determination of newly discovered NEOs in collaboration with ground-based optical and radar systems, reducing the need for actual deflection campaigns.

NASA should also examine the additional costs and observing advantages of a pair of such Venus-orbit survey telescopes, both to complete the overall survey more rapidly and aid in collapsing the error ellipse of worrisome NEOs. These enhanced capabilities may further reduce unnecessary launches of *in situ* tracking or deflection spacecraft.

Although some NEOs are potentially hazardous, their periodic close approaches to Earth also make them among the most accessible objects in the solar system for robotic and human exploration. A space-based IR survey telescope would efficiently find both exploration targets and threatening NEOs currently inaccessible to observation by ground-based systems.

2.2. Orbit Determination: NASA should plan and budget for the incremental costs of maintaining the Arecibo and Goldstone planetary radars to facilitate rapid orbit refinement and detailed physical NEO characterization.

For some of the most worrisome NEOs, the planetary radars can provide high-precision trajectory and physical properties information, potentially approaching that from a flyby spacecraft but at substantially lower cost. For a newly discovered object within range, ground-based radars can measure position and velocity accurately enough to predict Earth encounters several hundred years in advance, much longer than for orbits determined optically.

For the subset of objects that come within range, current radars are very effective at reducing NEO orbit uncertainty and associated impact potential. Delay-Doppler echoes can be used to distinguish almost immediately between an impact trajectory and a near miss for an observed NEO's next century of Earth encounters. This capability substantially reduces ambiguous predictions of an impact, and thus the difficulty and projected cost of any deflection efforts.

For a modest fraction of discovered NEOs, radar data can also detect binary systems, their orbits, and thus determine the component masses. Radar can help constrain some solitary NEO masses via measurement of thermal re-radiation accelerations (the Yarkovsky effect). With adequate observations, a radar image sequence can be used to construct a three-dimensional shape, define the rotation state, and determine spatial distribution of radar surface properties. Such physical information compares favorably to flyby measurements and can be of substantial value to Planetary Defense and mission planning activities.

2.3. Short-term Warning: NASA should investigate development of low cost, short-term impact warning systems and encourage widespread deployment, certainly by the international space agencies, and possibly by amateur and academic astronomical communities. Recent work has shown that relatively inexpensive, off-the-shelf telescope designs can provide short-term impact warnings. Coming just days or weeks before impact, such detections would aid civil defense efforts when deflection attempts are impractical. The NEO size-frequency distribution with many more small than large asteroids indicates that the most likely near-term damaging impact would be expected from an object 20 to 30 meters in size or somewhat larger. (In the event that even a small object, say a few meters in size, is discovered with a precise date and place of impact, it might be prudent to evacuate people or warn them to seek shelter). The limited coverage from current or planned search telescopes makes them incapable of discovering a significant fraction of these smaller objects (numbering in total about ten million), one of which is expected to strike Earth every 50 years on average. These events will garner great public attention and will likely demand a coordinated government response.

Relatively inexpensive, multiple telescope systems could discover about 60 percent of these objects on an impact trajectory days or weeks in advance of a collision, enabling effective evacuation and any disaster response. Both the early warning discovery data and prompt follow-up observations must be integrated into the existing NEO data cataloging systems (including the

Minor Planet Center, the clearinghouse for all NEO observations), and the orbit prediction and risk computation centers at NASA's Jet Propulsion Laboratory and NEODyS in Pisa, Italy.

With costs for some of these systems in the range of $1 million to $2 million per telescope, donations and/or modest NASA subsidies could enable universities or serious amateur astronomy communities to become a useful part of the agency's NEO warning system. Such low-cost systems would likely also educate the public and stimulate student interest in planetary defense.

Recommendation 3: Investigate the Nature of the Impact Threat.

To guide development of effective impact mitigation techniques, NASA must acquire a better understanding of NEO characteristics by using existing and new science and exploration research capabilities, including ground-based observations, impact experiments, computer simulations, and *in situ* asteroid investigation.

3.1. Physical Characteristics. NEO survey programs should provide initial physical characterization of discovered objects. These characteristics include size, reflectivity, and color brightness at wavelengths useful for interpreting first order mineralogical composition.

A key element in any defense strategy is to "know thine enemy." Although the motion of a newly discovered object can reveal whether the orbit is categorized as "potentially hazardous," the discovery images themselves contain little information about the NEO's physical nature. In many cases, an object for which follow-up physical characterization is urgently needed does not present another favorable observing opportunity for years. NEO characterization is an ongoing process that begins at the time of discovery. Obtaining basic characterization measurements immediately following discovery takes advantage of the same favorable observing geometry that enabled the NEO's detection. Simultaneous orbit determination and preliminary physical assessment of the object provides the earliest and most informed basis to evaluate any possible threat.

Objects classified as "potentially hazardous" should receive priority for follow-up physical observations from ground-based facilities. *In situ* characterization of these objects (see **3.2**) will provide independent verification of the assessments made from the ground. *In situ* verification of ground-based characterization capabilities will provide the highest level of confidence for dealing with any near-term NEO threat, for which ground-based measurements may provide the only characterization information available.

3.2. Planetary Defense Characterization Missions. NASA's science, exploration, and survey missions aimed at NEOs should include determination of the physical characteristics most directly related to Planetary Defense. These include size, mass, density, porosity, composition, rotation period, interior structure, binary nature, surface heterogeneity, and near-surface mechanical and thermal properties. Also useful for Planetary Defense planning are science and exploration mission objectives aimed at determining NEO internal structure and evaluating methods for coupling directly to its surface.

At this early stage in our understanding of NEOs, science and exploration mission objectives are highly commensurate with those required for Planetary Defense. These natural synergies between science, exploration, and Planetary Defense should be fully exploited for all missions to these solar system bodies. Understanding the physical diversity or similarity of NEOs over the size range of tens to hundreds of meters, with compositions varying from low-density carbonaceous "rubble piles" to high-density, monolithic nickel-iron bodies, will inform the range of mitigation strategies needed for effective planetary defense.

Recommendation 4: Prepare to Respond to Impact Threats.

To prepare an adequate response to the range of potential impact scenarios, NASA should conduct a focused range of activities, from in-space testing of innovative NEO deflection technologies to providing assistance to those agencies responsible for civil defense and disaster response measures.

4.1. Disaster Response. NASA should work with the Department of Homeland Security (DHS) and other relevant U.S. government agencies to assign roles and formulate plans for civil defense, such as evacuation of threatened areas, should NEO deflection prove impractical. The disaster management and response community should plan for the most likely impact scenario: a small (tens of meters in size) NEO striking with only days or weeks of warning. A transparent, effective, credible public communication plan is a high priority, to include topics such as the possible impact area, physical effects, and improved probability estimates as observations improve.

The disaster management and response community has not extensively dealt with the threat of NEO impacts, nor is NASA well-versed in the processes or needs of the civil defense community. NASA and the DHS should coordinate their mutual information needs for a NEO impact response as soon as possible.

4.2 Deflection Research Program. In parallel with impact disaster response planning, NASA should perform the necessary research and development to perform an in-space test of a deflection campaign, with the goal of modifying, in a controlled manner, the trajectory of a NEO. Such a demonstration program should include both a powerful impulse technique (e.g. kinetic impact) and a gradual, precise (e.g. gravity tractor) deflection capability.

With sufficient warning, existing technologies are likely adequate for NEO deflection but it is critical for both public and government confidence to physically demonstrate them prior to employment in an impact threat scenario. The European Space Agency, Russian Federal Space Agency, and others have examined and are planning NEO deflection missions, and NASA should aggressively pursue a cooperative deflection capability demonstration.

4.3. Explosive Technologies. Although nuclear explosives are considered a rarely needed and last-resort deflection option, it is prudent that NASA should collaborate with the Department of Energy and Department of Defense to develop an analytic research program to explore the applicability, utilization, and design of nuclear explosion technology for NEO deflection.

If a large NEO deflection demands a total impulse greater than that deliverable via multiple kinetic impactors, then detonation of a nuclear device in standoff or other mode may be necessary to avert an Earth impact. Until non-nuclear techniques of comparable capability are proven, NASA should collaborate in nuclear deflection technique analysis and simulation.

4.4: Deflection Physics. NASA should initiate both analytic and empirical programs to reasonably bound the "momentum multiplier" (termed "β") in kinetic impact deflection.

β is the key variable in determining kinetic impact deflection performance. The momentum multiplier describes the extent to which the momentum of ejecta blasted clear by the impact augments the momentum transferred directly to the NEO by the incoming projectile. This parameter is unlikely to be known precisely before an actual deflection, and current estimates vary by factors of five, ten, or more. The success of both mission planning and assessments of deflection feasibility depends strongly on bounding the value of β by analytic and empirical means.

Research should include computer hydrocode impact simulations, laboratory gas gun tests, and other appropriate experiments aimed at better understanding the momentum transferred to a target by a kinetic impactor. The sensitivity of the momentum enhancement factor (β) to the target's composition and structure should be examined, along with the scaling expressions appropriate for impacts at varied velocities and encounter geometries.

4.5. Impact Scenarios. NASA should develop a reference set of a few impact threat scenarios and a corresponding set of deflection campaign design reference missions. These reference deflection scenarios should be shared nationally and internationally, forming the basis for future impact gaming exercises.

Such impact threat and response scenarios should reinforce the concept that many NEO deflections will result in near-misses occurring periodically in future years on nearly the same calendar day, because the NEO and Earth orbits nearly intersect at that point. At each close-approach, Earth's gravity will deflect the NEO into a new orbit that will again encounter the Earth's orbit and possibly a number of nearby "keyholes" (small regions in space near Earth through which a passing NEO may be gravitationally redirected onto a path to impact Earth). To preclude such a future keyhole passage and subsequent Earth collision, each deflected NEO will need periodic monitoring to determine if some orbital fine-tuning is required.

Recommendation 5: Lead U.S. Planetary Defense Efforts in National and International Forums.

NASA should provide leadership for the U.S. government to address Planetary Defense issues in interagency, public education, media, and international forums, including conduct of necessary impact research, informing the public of impact threats, working toward an internationally coordinated response, and understanding the societal effects of a potential NEO impact.

The NEO hazard exists within the context of other natural and technological hazards, and that lens of experience shapes citizens' and decision-makers' perceptions. As extreme examples of low-probability, high-consequence events, NEO impact threats are especially susceptible to misperception. Few people have witnessed even a small impact into Earth's surface, yet there is substantial and growing awareness that a devastating NEO impact is possible.

5.1. Societal Leadership. NASA should lead U.S. government efforts, in public and international forums, to educate, coordinate and act in reducing the threat of a NEO impact. With its broad expertise on the nature of the NEO hazard, NASA should cooperate with other elements of society that study, report on, and make decisions about NEO threats. Such societal elements include, but are not limited to:

- Media reporting newsworthy NEO developments and events
- The hazards community, including civil defense agencies and emergency responders
- Military elements with interests and responsibilities for national security space and disaster relief activities
- Educational institutions (including popular institutions like science museums) responsible for developing an informed citizenry
- Scientific communities (beyond the astronomical field), which have the expertise to undertake research on the physical, environmental, societal, and economic effects of threatened or actual impacts
- The space law community, which may be called on to apply legal principles developed in other contexts to the unique circumstances of a NEO impact threat
- Political leaders responsible for responding effectively and rapidly to unusual events affecting society

5.2. Impact Effects Research. NASA should support research addressing the breadth of physical, environmental, and social consequences of a range of NEO impact scenarios. With its investigation of the NEO hazard, NASA has interests in understanding impact consequences not deeply shared by other U.S. scientific agencies. More research is needed on Earth's atmospheric response to large impacts during NEO entry and subsequent lofting of ejecta into the atmosphere. The same is true for the direct impact effects on the landscape and human infrastructure, adding to the limited understanding gained from nuclear test data of a half-century ago. Ocean impacts and the characteristics of impact-generated tsunamis require further study. NASA should also investigate the psychological and sociological consequences of a NEO impact, given how unfamiliar such disasters are to the public.

5.3. Impact Simulation. NASA and other PD-relevant agencies should develop representative impact threat timelines (linked to reference deflection missions), and initiate periodic multi-agency response simulations and evaluations. NASA must proactively extend its NEO impact knowledge to coordinating agencies, especially those responsible for disaster response, such as the DHS.

Coordinated table-top exercises will be an essential training and evaluation tool in inter-agency impact threat preparations. A detailed impact scenario timeline from early detection to successful deflection or civil defense response will be the nucleus for any exercise. A set of such timelines, representing a plausible variety of cases and consistent with a set of design reference missions (see **4.5**) will serve as an essential, multi-agency planning resource.

5.4. Communications Plan. NASA and other relevant agencies should collaboratively develop a comprehensive Planetary Defense public communications plan. Transparent communication in any potential or real disaster scenario is essential, both within responsible agencies and to the general public. Given that the public has little or no intuitive experience with impact threats, it is critical that NASA authoritatively communicate information about a future event.

NASA's plan should anticipate the evolving public demand for information throughout an impact threat scenario from initial warning through deflection campaign completion or actual impact. Taking full advantage of the avenues available in this information age, the plan should start with the early establishment of a broadly based informational and educational structure (see **5.6.**) concerning the general nature of the impact hazard. NASA's plan should further develop and promulgate tools conveying the seriousness of a threatened impact, including calculation and publication of relevant risk corridors for NEOs posing a serious threat.

The plan should assume and accommodate a parallel effort at the international level because of the global implications of some NEO impact threats level (see Schweickart et al.). Close coordination will be essential in providing clear, consistent, authoritative, and trustworthy impact information to the public.

5.5. Legal Implications. NASA should utilize national and international expertise to develop the legal basis for potential actions related to Planetary Defense. This analysis should include liability and other implications, including impact warning or failure to warn, nuclear explosive use, and any actions that alter the orbit of any potentially hazardous asteroid.

The international and space law basis for many aspects of NEO impact threat response is not well understood. Initial investigations have already begun at the international level through initiatives within UN COPUOS. NASA and U.S. participation in development of or adaptation of existing legal instruments is essential.

5.6. Public Education and Outreach. As the warning agency for Planetary Defense, and possessor of most information about NEOs, NASA should establish a public education and outreach program to inform government officials and the general public about NEO impact hazards and mitigation options. This program should engage experienced social and behavioral science practitioners, as well as professional and informal educators. For example, methods used by meteorologists to communicate the probable paths (and prediction uncertainties) of hurricanes might be applied to informing the public of the risk of a possible asteroid impact.

A proactive program of public and media education about essential elements of the NEO impact hazard and potential responses would be valuable, particularly in countering public misunderstanding. Public education would go far in countering accidental misunderstandings, accidental or purposeful spread of misinformation, and the susceptibility of some to alarmist or catastrophist interpretations. Without such an education initiative, the loss of public confidence will likely prove very costly.

Conclusions

NASA has developed a strong foundation for understanding the NEO hazard and building a long-term capability to counter a potential asteroid impact threat. By taking the steps recommended in this report, the agency can expand this expertise and lead global efforts to develop an effective capability for Planetary Defense.

Society now possesses sufficiently mature space technology to provide two of the three elements necessary to prevent future damaging asteroid impacts. NASA currently searches for the largest objects of concern and issues warning information for any asteroid discovered to approach Earth. New ground- and space-based search systems can increase our capability to provide impact warning for the smaller, more numerous asteroids. Although NASA has not demonstrated a specific asteroid deflection capability, the agency's current spaceflight technology shows that impact prevention is possible. Actual NEO deflection demonstrations are being studied and are excellent candidates to be part of future NEO science and technology missions.

The missing third element for NEO impact prevention is the international community's readiness and determination to respond to a predicted future asteroid collision with Earth. NASA is wellpositioned to take a leading role in this government and international response, but to be ready, the agency must move well beyond search, analysis, and warning to develop the practical means for actually changing a threatening asteroid's orbit.

Without the ability to detect the most numerous asteroids, to alter NEO orbits, and to lead a global effort to plan a deflection campaign, the only possible U.S. response would be evacuation and disaster response. If NASA fails to prepare for Planetary Defense, and then a sizeable random NEO strikes Earth without warning, the damage to the U.S.'s leadership and reputation would swell the tally of the event's devastating effects. NASA should begin work now on forging its warning, technology, and leadership capacities into a global example of how to effectively shield society from a future impact.

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List of Acronyms

COPUOS	United Nations Committee on the Peaceful Uses of Outer Space
DHS	U.S. Department of Homeland Security
DoD	Department of Defense
DoE	Department of Energy
IR	infrared
LSST	Large Synoptic Survey Telescope
NAC	NASA Advisory Council
NASA	National Aeronautics and Space Administration
NRC	National Research Council
NEA	Near-Earth Asteroid
NEO	Near-Earth Object
NEC	Near-Earth Comet
OSTP	Office of Science and Technology Policy
PanSTARRS	Panoramic Survey Telescope and Rapid Response System
PD	Planetary Defense
PHA	Potentially Hazardous Asteroid
UN	United Nations

Appendix

NASA ADVISORY COUNCIL

AD-HOC TASK FORCE ON PLANETARY DEFENSE

TERMS OF REFERENCE

The Ad-Hoc Task Force on Planetary Defense (hereinafter, "Task Force") is a task force of the NASA Advisory Council, supporting the advisory needs of the NASA Administrator, the Exploration Systems Mission Directorate (ESMD), the Space Operations Mission Directorate (SOMD), and other NASA Mission Directorates, as required. The scope of the Committee includes all NASA programs, projects, activities, and facilities related to Planetary Defense.

Per NASA Policy Directive (NPD) 1150.11, *Federal Advisory Committee Act Committees,* the Task Force will be managed under procedures that ensure the same spirit of openness and public accountability that is embodied by the Federal Advisory Committee Act (FACA). This includes public meetings as appropriate and public access to Committee records.

MEMBERSHIP

The membership of the Task Force will consist of leading authorities with relevant expertise drawn from industry, academia, independent researchers, and Government institutions. The Administrator, in consultation with the Council Chair, will appoint the members and the Task Force Co-Chairs. Appointments will be for a two-year term, with reappointment and replacement at the discretion of the Administrator, made in consultation with the Council Chair. The Task Force will have between 5-15 members.

MEETINGS

The Task Force will meet on an as-needed basis. Task Force meeting agendas will be approved pursuant to NPD 1150.11, by the Task Force Executive Secretary, after coordination with the Task Force Co-Chairs, and will be responsive to requests from the Administrator, the Council Chair, the ESMD Associate Administrator, and the SOMD Associate Administrator. The annual NASA Advisory Council Work Plan will serve as the primary source of priorities for the Task Force meeting agendas. The Task Force Co-Chairs will attend Council meetings as appropriate. The Executive Secretary of the Task Force will publish notices of upcoming Task Force meetings in the Federal Register no less than 15 days prior to each meeting.

REPORTING

The Task Force Co-Chairs will report on the Task Force's findings, observations, and draft recommendations to the Council at the Council's public meetings for deliberation. Records of each Task Force meeting, including meeting agenda, list of attendees, minutes, and presentations will be kept by the Task Force Executive Secretary. The meeting agendas and presentations from Task Force public meetings will be provided to the Council Executive Director for posting to the Council Web site for public access. After certification of the minutes by the Task Force Co-Chairs and the Task Force Executive Secretary (not to exceed 90 days following the meeting, but preferably within 14 days), the minutes will be provided to the Council Executive Director for posting to the Council Web site for public access. In addition, the Task Force Executive Secretary will keep detailed financial records, member appointment records, and other pertinent records throughout the year and provide annual summary input on the Task Force's activities to the Council Executive Director for NASA's required annual fiscal year report to the General Services Administration on its FACA advisory committees.

ADMINISTRATIVE PROVISIONS

The Task Force Executive Secretary will be jointly appointed by the ESMD Associate Administrator and the SOMD Associate Administrator, in consultation with the Task Force Co-Chairs and the Council Chair, and following coordination with the Council Executive Director. The Executive Secretary of the Task Force will work with the Task Force Co-Chairs to coordinate meetings, agendas, speakers, etc. for Task Force meetings. Staff support and travel funds for the Task Force Co-Chairs and members will be provided jointly by ESMD and SOMD. Other NASA Mission Directorates may provide support for specific activities, as appropriate.

DURATION

The Task Force terms of reference will be evaluated every two years at the time of formal renewal of the NASA Advisory Council Charter and are subject to formal renewal at that time by the Administrator. If the Council's Charter is terminated or expires, the Task Force will terminate. The Task Force may be terminated at the discretion of the Administrator. If the Task Force terminates, the Task Force terms of reference also terminate, and all appointments to the Task Force terminate.

(signed)
Charles F. Bolden, Jr.
NASA Administrator
September 9, 2010