The scientific opportunities of a General Astrophysics program associated with a Dark Energy Mission

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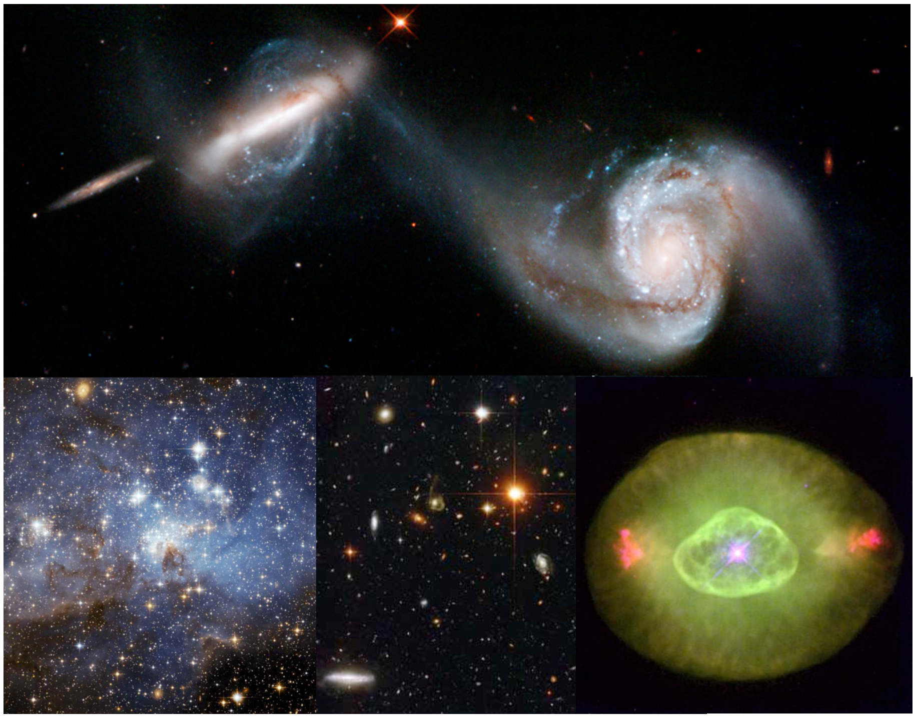

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Executive Summary

One of the high priorities in the astronomical community for the next decade is to launch a space observatory to probe the nature of dark energy through measurements of weak lensing, baryon acoustic oscillations and high redshift supernovae. Until recently, this mission was conceived of as a joint NASA/DOE dark-energy mission (JDEM). It may well become an International Dark Energy Cosmology Satellite (IDECS), but we will use JDEM as the shorthand in this document. This mission will represent the first true foray into space-based wide-field, high angular-resolution, far-red optical and near-infrared imaging and spectroscopy. Besides providing a more in-depth understanding of dark energy, the JDEM datasets have the potential to revolutionize key areas across the gamut of astrophysical research. Here, we outline the case for the addition of General Astrophysics Guest Investigator and Guest Observer programs. Implemented from the outset as an integral part of the JDEM design, these programs will offer a crucial opportunity to significantly increase the overall scientific impact of the mission and to expand greatly the community of astronomers supporting it. Experience with missions such as the Hubble Space Telescope (HST), Chandra, Spitzer and GALEX and ground-based projects such as the 2-Micron All-Sky Survey (2MASS) and the Sloan Digital Sky Survey (SDSS) has demonstrated that the overall scientific impact is critically tied to the breadth of the community served.

This paper outlines several methods of implementing a General Astrophysics program within JDEM. As a bare minimum, we advocate that JDEM is structured such that the data are processed and archived in a manner that permits archival Guest Investigator programs. In addition, we propose modes of implementing a Guest Observer program: in conjunction with the core dark energy program, and fully integrated with survey observations, as in the Kepler or GALEX missions; or implemented as an extension to the core mission.

Many HST and SDSS scientific successes were not planned during the conception and project design. What was planned was the flexibility to enable scientific discoveries beyond those required for the core mission objectives. This flexibility can be achieved with JDEM at little extra cost to the mission if a General Astrophysics program is conceived, configured and included explicitly in the early phases of the mission design.

We hope that the Astro2010 Decadal Survey will encourage NASA to ensure that JDEM, if selected for further development, is implemented in a manner that enables General Astrophysics and maximizes the scientific return from the mission.

1. Key Science Goals

The scientific impact of a General Astrophysics program

The broad scientific potential of JDEM observations was highlighted in the National Research Council's BEPAC report, which states: "The wide field optical and near infrared surveys required for dark energy studies will create large, rich data sets useful for many other astrophysics studies, enlarging an already significant discovery potential."

A General Astrophysics program can act as a powerful force multiplier for the overall scientific impact of focused research projects. Survey datasets can address multiple science goals, provided they are designed at the outset with a broad goal in mind. As a secondary benefit, General Astrophysics programs widen the JDEM constituency, opening direct participation to a much wider cross section of the astronomical community. This ensures a higher degree of support through the different phases of mission development, which could be crucial in times of financial uncertainty.

Specific examples of the power of ancillary science come from the experience of the Hubble Space Telescope (HST) and the Sloan Digital Sky Survey (SDSS).

HST was conceived with the key task of refining the value of the Hubble constant, H_0. It has achieved that goal: at launch in 1990, the scientific literature held estimates of H_0 ranging from 50 to 90 km s^{-1} kpc^{-1}, each stated with nominal uncertainties of better than 10%. Following more than a decade of observations and analysis, the Hubble Constant Key Project resulted in a generally accepted value of H_0=72±8 km s^{-1} kpc^{-1}, with dissenting values within 20\% or 1.5σ. These values are consistent with recent constraints from WMAP. But HST has achieved a scientific impact that reaches far beyond this single parameter. Of the ~7000 refereed publications generated from HST data over the last 17 years, fewer than 2% are directly related to measuring H_0. At the same time, HST Guest Observer programs have made fundamental contributions across the astronomical spectrum from planetary science, through stellar astronomy to galaxy evolution and cosmology, including key issues that were unforeseen at HST's launch, such as transiting exoplanets and dark energy itself.

Similarly, SDSS was conceived primarily as a million-galaxy redshift survey designed to probe large-scale structure, and that goal was achieved by the initial survey. But the SDSS multicolor datasets, covering almost 25% of the high-latitude sky with unprecedented photometric accuracy and depth, have led to breakthroughs in such diverse areas as codifying the origin of Solar System asteroidal families, conducting a census of ultracool low-mass stars and brown dwarfs, mapping sub-structure and tidal features within the Milky Way Galaxy and identifying new dwarf companions of Local Group galaxies, probing the Lyman α forest through quasar spectroscopy, detecting the first quasars at redshifts $z>5$, and the first measurement of acoustic oscillation signatures in galaxy clustering. Papers on these ancillary topics account for more than 85% of SDSS refereed publications. It is interesting to underline that studying baryonic acoustic oscillations was not in the original suite of science goals for SDSS, but became, after the fact, one of the most remarkable results of the survey.

JDEM has the power to address a similarly wide range of scientific issues beyond dark energy, directly engaging the same communities that have used HST and SDSS. The Hubble community will form a natural, broad constituency that will rally to support of the JDEM project if they are convinced that the mission will support their science.

Unique JDEM Capabilities

The full JDEM capabilities are still under development. However, the baseline mission envisages a ~1.5-meter telescope that will undertake wide-field imaging covering thousands of square degrees at far-red and near-infrared wavelengths (0.7 to ~2 μm) to 25th magnitude at angular resolutions better than ~0.2 arcseconds, and spectroscopy covering tens of thousands of square degrees at sufficient resolution to allow redshift measurements for 10^8 galaxies. JDEM will also conduct photometric monitoring of tens of square degrees to search for supernovae. The projected mission lifetime is at least 5 years.

The baseline mission will provide unique opportunities for astrophysical investigations beyond dark energy. Other past and future near-IR imaging surveys span a wide range of parameters, from all sky-surveys at moderate depth (e.g., 2MASS, WISE) through deeper surveys over smaller areas (e.g, VIKING) to very deep pointed observations of small sub-degree fields (e.g.,with HST/WFC3 or JWST/NIRCam). By comparison, JDEM will provide a unique combination of area and depth. This will provide researchers with statistically significant samples of objects that are too faint and/or too rare to be picked up in large numbers in the other surveys. In the far red, the imaging capabilities of JDEM will overlap with LSST and Pan-STARRs, which span wavelengths of 0.3-1.1 μm. While the surveys cover comparable areas, JDEM is likely to have better angular resolution and higher stability. JDEM and LSST are likely to reach comparable depth at ~0.8 μm, and the near-IR coverage of JDEM will allow it to probe highly-reddened and high-redshift populations of objects that are accessible to LSST. JDEM will include spectroscopy, which would be a very important complement to the ground-based campaigns.

In summary, JDEM will occupy a unique parameter space in terms of wavelength coverage, areal coverage, photometric depth, angular resolution, and availability of spectroscopy. As a space mission, it is also likely to have astrometric, photometric, and spectrophotometric stability that cannot be matched by ground-based surveys. All of this suggests that JDEM will enable unique science well beyond the core subject of dark energy. Moreover, the scientific potential of any JDEM data set can be further enhanced by combination with results from other surveys, creating a fertile ground for potential archival research.

Science programs with JDEM

We list examples of science programs that can take advantage of JDEM observations. Some of these programs can be carried out using only JDEM survey data; others can profit significantly from additional observations.

Trans-neptunian objects in the Solar System: Our understanding of the outer Solar System has been transformed over the last decade, with the growing realization that Pluto is one of many icy objects within the Kuiper Belt. Ground-based observations have proven effective in identifying the brightest (largest) trans-neptunian objects (TNOs), but JDEM can extend observations to fainter, lower-mass objects, complementing ground-based optical surveys such as LSST and Pan-Starrs, and probe the TNO mass spectrum and orbital distribution. The mass spectrum and its correlation with orbits offers an important record of the processes that shaped our solar system and presumably others.

An ultracool dwarf census: The last decade has seen a revolution in cool-star astrophysics, with the identification of objects later than spectral type M. Ground-based surveys have pushed observations to objects with surface temperatures cooler than 700K. These objects have strong, distinctive near-infrared spectral features and extreme colours. JDEM spectroscopy and photometry could be crucial in extending coverage to even cooler dwarfs, covering a larger volume than WISE, probing their atmospheric structure and defining the initial mass function well below the substellar limit.

Stellar populations in the halos of nearby galaxies: Observations of the Galactic halo have revealed significant substructure, including tidal streams that can be used to constrain CDM galaxy formation models. A thorough test of those models requires imaging the entire halos of hundreds of galaxies, a task that requires angular resolution and sensitivities beyond the scope of ground-based observatories. HST has contributed, with partial coverage of the M31 halo and a handful of other nearby galaxies, but the observations are extremely time-consuming. JDEM can make a major contribution to this subject, particularly if the archival data are enhanced by a modest pointed GO program.

Variability and transiting exoplanets: JDEM will make repeated observations of several few-square-degree fields to search for high redshift supernovae. Those data can also be used to identify other variable objects, including eclipsing binary stars, cataclysmic variables, pulsating variables, microlensed sources, variable active galactic nuclei and new types of photometric transients. Indeed, the photometric stability provided by JDEM could be sufficient to permit detection of transiting giant planets. Since the JDEM observations are concentrated at high galactic latitudes and faint, near-infrared magnitudes, the overwhelming majority of targets are halo stars or extragalactic sources, complementing ground-based optical surveys that also cover the Galactic disk. All of these variability surveys would be enhanced by a supplementary JDEM pointed program that would increase the observational cadence, and probe the nature of novel sources.

Galaxy formation in the high redshift universe: The combination near-infrared photometry from JDEM with comparably deep optical photometry from JDEM or from an LSST-like survey, will greatly reduce both the scatter and the bias in photometric redshift estimates for faint galaxies. The broad wavelength coverage will also improve constraints on stellar populations and dust content. Near-infrared photometry over wide areas will allow searches for galaxies and QSOs out to $z\sim12$, tracing the evolution of the most luminous objects in the universe. JDEM could provide vital synergy with LSST, measuring galaxy evolution and galaxy clustering as a function of redshift. Those observations do not demand a well-sampled PSF, but do require high-accuracy photometry of barely resolved sources.

Star formation as a function of redshift: Our understanding of the evolution of the star-formation rate vs. redshift is still sketchy. In the redshift range z~1–2, different surveys disagree by factors of 3 or more in the globally averaged star-formation rate density, even when using the same tracer (e.g. UV, H-alpha or infrared). A JDEM spectroscopic survey can provide Hα luminosities for 10^8 galaxies, together with emission measurements for other species such as [O II] and [O III]. This will provide exquisite tracking of the star-formation rate and the distribution of chemical abundances as a function of galaxy type and redshift. It will also trace the evolution of galaxy nuclear activity and galactic morphology. JDEM deep spectroscopic pointings will be extremely valuable as well, yielding ~10^5 galaxies down to Hα fluxes ~10^{17} erg cm^{-2} s^{-1}, which is a far larger blind survey than can be done without huge allocations of JWST time. These would make enormously valuable contributions to studying the star-formation history as well as providing an essential calibration of photometric redshifts of all space and ground observations.

Large-scale structure as a function of redshift: Combining JDEM and LSST imaging with JDEM spectroscopy will enable construction of detailed maps of galaxy density from both clustering and lensing measurements. Near-infrared photometric data from JDEM can greatly improve photometric redshift estimates relative to those obtained from optical images alone. Those data can be used to investigate the growth of structure with redshift, connecting galaxy evolution and dark-matter halos.

Strong lensing by galaxy clusters: Galaxies and clusters can act as gravitational lenses, magnifying and distorting the images of background galaxies. The morphologies of those images can be used to map the mass distributions the foreground objects, while the lensed galaxies themselves serve as probes of the high redshift universe. Current high-resolution observations cover a few dozen clusters, and about 200 galaxy-scale lenses. The JDEM survey data could enable strong lensing measurements of ~10^4 galaxies and a few hundred of the most massive clusters, while a targeted GO program could obtain deeper imaging data for hundreds of clusters. Because of its better angular resolution, JDEM can measure image shape for more galaxies per square arc minute than possible from the ground, providing higher resolution lensing mass maps and a greater abundance of galaxy-scale lenses. The wide-field cluster images will allow combined weak and strong lensing analyses on an industrial scale. This resolution is particularly important for identifying multiple source plane “compound” lenses, which provide strong constraints on density profiles and the geometry of the Universe. The deep NIR imaging capability opens the possibility of detecting very high redshift lensed galaxies – cosmic telescopes provide the best opportunities for studying these systems in detail.

Active galaxies at very high redshift: Slitless spectroscopy over a wide field will provide a sensitive search for luminous AGN at very high redshifts. The Lyman α forest break will be a prominent feature, making identification easy for objects $8<z<12$ for a spectrograph running from 1–1.7 μm. JWST cannot provide sufficient areal coverage to identify these rare objects, and ground-based instruments are not sensitive enough. JDEM survey data alone will enable significant breakthroughs in this area.

A May 2004 meeting on "Wide-Field Imaging from Space" in Berkeley discussed a wide range of additional astrophysical programs where JDEM can make a significant contribution. The proceedings of this meeting appeared as Volume 49, Issues 7-9, Pages 335-486 (November 2005) of New Astronomy Reviews (McKay, Fruchter, Linder, eds.).

2. Implementing a General Astrophysics Program

General Astrophysics programs have been incorporated in plans for other specialized NASA missions, including GALEX, Kepler and SIM-Lite. A fraction of the mission time is allocated to Guest Observer (GO) programs through competitive peer review. In the case of JDEM, the "competed" GO time could be used for additional dark energy studies, and/or a broader suite of astrophysical applications. Thus, GO time can not only broaden the overall scientific return, but also provide the flexibility to enable *other* dark energy programs with different approachs that may follow future developments in the field . Indeed, if the JDEM mission parameters are tuned too tightly based on our current ideas about dark energy, there is a risk that the mission will have difficulty in adapting to the evolution in our understanding. *Thus, reserving a modest fraction of the core mission as contingency for future allocation can be viewed as prudent risk management.*

JDEM's prime mission is to investigate dark energy. General Astrophysics should therefore not be allowed to drive major aspects of the JDEM mission design, but when decisions are made, other considerations being equal, the implications for ancillary science should be taken into account. For example, the survey should be designed acknowledging that broader scientific applications could potentially set different calibration requirements than dark energy programs. Consequently, to be fully effective, it is vital that the General Astrophysics component is conceived as an integral part of JDEM from the outset. This integration must be present at all levels, from scheduling observations, through calibration, to archival services.

JDEM data products should be processed and archived in a manner that enables broad exploitation of the datasets. As an extreme example, one might envisage a specialized pipeline analysis of imaging data that focused solely on constraining weak lensing through measuring galaxian orientations, at the expense of processing the data to allow accurate photometry and morphologies. Similarly, a spectroscopic pipeline that produced only galaxy redshifts would not facilitate any analysis of galactic metallicities and/or star formation rates. Care must be taken in the pipeline processing to retain all data that, though not directly relevant for the goals of a core dark energy team, could enable deeper insight in other areas of astrophysical phenomena.

JDEM data products should be made available to astronomical community as rapidly as possible. This is particularly true if JDEM is operating simultaneously with ground-based synoptic surveys, such as LSST or Pan-Starrs. Rapid data dissemination also enables detailed follow-up observations with ground- or space-based facilities. For example, TNOs, photometric transients and microlensed sources must be identified rapidly (a matter of days) to enable adequate follow-up observations. Maximizing the scientific return demands giving a broad community early access to the data. Should it be deemed programmatically necessary to restrict access to data associated with specific JDEM investigations, then the appropriate controls can be set within the data archive.

A JDEM General Astrophysics program can be constructed in a number of ways. We consider three scenarios:

1. A Guest Investigator (GI) program, where 100% of the mission is devoted to pre-specified dark energy survey programs, but access to the JDEM data is provided to the

wider astronomical community for programs that are different in scope from the original survey. The models for this mode of operation are ground-based surveys such as SDSS or 2MASS, or space mission data archives such as the Multi-mission Archive at Space Telescope (MAST).

2. An Integrated Guest Observer Program, where a modest fraction of the mission time is allocated by competitive peer review. The GO observations are integrated within the overall JDEM dark energy programs. The models for this mode of operation are the Kepler mission and the GALEX mission.
3. An extended JDEM mission, with a substantial fraction (at least half) of the additional years devoted to observations for GO programs.

These scenarios are neither exhaustive nor mutually exclusive. In particular, we advocate that a GI program should be implemented in tandem with any GO program.

Case 1: An Archival Guest Investigator Program

The National Research Council's BEPAC report emphasized the importance of providing broad access to the data collected in the course of the JDEM survey. Specifically, the report states: "JDEM will produce an extraordinary database that, properly archived and made available to the community in a timely manner after acquisition, will provide the basis for a broad archival research program leading to opportunities for unexpected discoveries in many areas of astrophysics."

Calibration techniques and processes will need to be screened carefully to ensure that they allow full exploitation of the JDEM datasets. For example, flat fielding techniques that are adequate for the detection of supernovae and/or weak lensing measurements may preclude photometry at the highest level of precision enabled by the data, and hence exclude ancillary science programs such as searches for planetary transits. In addition, specialized GI programs may require specialized post-processing of the data, and the archive must be established in such a manner that enables the customized processing and analysis required by such specialized programs.

We anticipate that JDEM archive data will be a major resource for the scientific community. This expectation is supported by our experience with Hubble: fully half of the current Hubble publications each year are based on archival data. A robust JDEM archival program, possibly with grant support for large-scale archival projects that exploit the trove of JDEM survey data, will be a major factor in driving future research. There will undoubtedly be discoveries from the JDEM data alone, but probably many more from the combination of JDEM data with data from other facilities. Spectacular science can be enabled at modest cost by creating a highly capable archive. The downside of a purely archival general astrophysics program is that there would be no opportunity for the community to propose observations.

Case 2: An Integrated General Observer Program

Many ancillary scientific programs either require or benefit from additional observations. A robust general astrophysics program could be established with less than 25% of the observing time. General astrophysics is best served if there are multiple proposal opportunities throughout the mission, rather than concentrating the opportunity into a single Announcement of Opportunity (AO) in advance of launch or concentrating all of the GO time at the end of the mission. The proportion of time devoted to GO programs can vary throughout the mission, but it is important to provide an opportunity to use the facility for high-priority non-dark-energy science early on. The experience gained in these early GO programs will help to refine the calibrations and user support for later cycles. Proposals submitted in response to the AO would be subjected to peer-review by a Time Allocation Committee and technical review by the JDEM Science Operations Center (SOC). Successful proposals would be integrated into the overall observing schedule throughout the core mission.

This mode of operation provides the astronomical community with an opportunity to react to new developments, whether in dark energy or general astrophysics, and propose programs that supplement the core survey observations and the initial round of GO programs.

Under this scenario, we also envisage the establishment of a data archive and an archival GI program; data obtained for GO programs might be protected from general access for a limited period.

Case 3: An Extended Mission

Finally, we consider the option of focusing exclusively on dark energy survey programs for the first 5 years of JDEM, but devoting at least half of the time to general astrophysics in a 2-3 year extension of the mission. The advantage of this approach is that the core science programs receive highest priority and the costs of general user support can be deferred. The primary disadvantage is missed scientific opportunities. Some events may not be repeated (e.g. rare astronomical events or the ability to carry out coordinated observations with a limited-lifetime facility). Furthermore, with only one or two years to propose GO observations, there is almost no opportunity to learn from the initial observations and plan follow-up observations.

3. Incremental Cost Estimates

The activities advocated in this paper are contingent on NASA's decision to pursue a Joint Dark Energy Mission in the next decade. If JDEM is selected, the baseline funding will include facilities and staff for scheduling and operating the telescope, and for establishing and maintaining the data archive. The BEPAC estimated full life-cycle costs for those missions to be between \$1.1 and \$1.3 billion dollars. Because the instrument characterization, calibration and data-reduction pipelines and archiving facilities needed for a General Astrophysics science program would be the same as needed for the core dark energy science program, we anticipate that the bulk of the costs for operations, archival development and support can be covered by the baseline funding. Here, we use analogies with current facilities to estimate the additional resources likely to be required to enable full exploitation of those additional capabilities.

Case 1: JDEM is expected to generate ~1 petabyte, or 10^{15} bytes, of data. This is only an order of magnitude larger than the data currently held in MAST at STScI, and we can anticipate significant advances in storage and data access technologies by the time that the JDEM data archive is defined. The current annual budget for maintaining and operating MAST and the Hubble Legacy Archive is ~\$2.5 million. JDEM must establish an archive as part of the baseline mission, so this represents an upper limit for the additional budget to maintain a set of software interfaces providing data access for general users.

A Guest Investigator program, funded at a level of ~\$2-3 million per year, comparable with current funding for HST archival research, will provide users with the opportunity to develop additional tools that can further exploit the database. This program can be implemented in conjunction with any of the GO programs discussed further below.

Case 2: Enabling a Guest Observer Program will require establishing an infrastructure to run Time Allocation Committees, provide user support and administer a grants program. Using the Kepler and GALEX programs as guides, we anticipate that the infrastructure costs are likely to amount to less than \$2 million/year.

The level of grant funding will depend on the fraction of time available for GO programs: taking the levels listed for HST, Chandra and Spitzer in the NRC Report "Portals of the Universe" (Table A.1) as a reference for a reasonable funding level, an allocation of ~25% of the observing time to GO programs is broadly consistent with a grants programs of ~\$5 million/year.

Case 3: Destiny, one of the three dark energy proposals considered by the BEPAC panel, included an estimate of the costs of funding an extended mission that would support General Astrophysics programs. The cost of supporting the Science Operations Center, including additional GO user support, for an additional 2.5 years was estimated as ~35 FTEs/year, corresponding to a total budget of \$20-25 million, excluding grant funding for GO programs. For comparison, the GALEX extended mission is funded at ~\$10M/year.

Under all three scenarios, we estimate that the additional costs incurred in supporting General Astrophysics amount to no more than ~4% of the total mission costs estimated for JDEM in the BEPAC report. **We argue that, if JDEM is supported by the decadal survey, the**

substantial increase in scientific impact offered by a General Astrophysics capability strongly justifies this marginal increase in cost.

Summary

JDEM is to provide the first comprehensive approach to understanding dark energy. We strongly believe it has the potential to revolutionize general astrophysics as well.

The addition of a General Astrophysics program, implemented from the outset as an integral part of the JDEM design, offers a key opportunity to significantly increase the overall scientific impact of the mission and to expand, by orders of magnitude, the community of astronomers supporting it.

The key factor is to plan the mission with the flexibility required to enable scientific discoveries beyond those required for the core mission objectives. This flexibility can be achieved with JDEM at little added cost to the mission, provided that a General Astrophysics program is conceived, configured and included explicitly in the early phases of the mission design.