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Measuring the Elemental Composition of Phobos: The Mars-moon Exploration with GAMMA rays and NEutrons (MEGANE) Investigation for the Martian Moons eXploration (MMX) Mission

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Earth and Space Science

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Earth and Space Science



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Key Points:

- The MEGANE investigation will measure the elemental composition of Mars' moon Phobos using gamma-ray and neutron spectroscopy
- MEGANE is part of the Japanese Martian Moons eXploration mission that will orbit Phobos then return a sample of Phobos to Earth
- By measuring the composition of Phobos, MEGANE will help resolve the question of whether Phobos is a captured asteroid or the remnant of a giant impact into Mars

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Measuring the Elemental Composition of Phobos: The Mars-moon Exploration with Gamma rays and Neutrons (MEGANE) Investigation for the Martian Moons eXploration (MMX) Mission

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Abstract The Mars-moon Exploration with GAMMA rays and NEUTRONS (MEGANE) investigation will use gamma-ray and neutron spectroscopy to measure the elemental composition of Mars' moon Phobos. MEGANE is part of the Japanese Martian Moons eXploration (MMX) mission that will make comprehensive remote sensing measurements of both of Mars' moons Phobos and Deimos. MMX will also return to Earth regolith samples of Phobos. The science goals of the MEGANE investigation mirror those of the MMX mission. MEGANE will use elemental composition measurements to determine if Phobos is a captured asteroid or the end result of a giant impact event on Mars, study Phobos surface processes, provide reconnaissance to support the sample site selection, and supply compositional context for the returned samples. To accomplish its measurements, MEGANE will use a high-purity Ge gamma-ray spectrometer (GRS), and a neutron spectrometer (NS) that consists of two ³He gas proportional neutron sensors. The GRS derives heritage from similar instruments from NASA's MERCURY Surface, Space ENVIRONMENT, GEOchemistry, and Ranging mission and the Psyche mission that is currently in development; the NS is based on similar instruments used for NASA's Lunar Prospector and Psyche missions.

1. Introduction

The inner solar system contains three moons, two of which – Phobos and Deimos – orbit Mars. Compared to what we currently know about Earth's Moon, which is believed to have formed following a giant impact on Earth, our understanding of Phobos and Deimos is relatively sparse. Their shape and spectral reflectance properties resemble outer solar system objects, suggesting an origin as captured asteroids. Yet dynamical accretion theories suggest they formed in the vicinity of Mars. A comprehensive exploration of both bodies has still not been accomplished and promises to significantly add to our understanding of early solar system evolution, in particular the processes that lead to the formation of moons around terrestrial planets (Murchie et al., 2015).

The fundamental question regarding Phobos and Deimos concerns how they came to be in orbit about Mars; namely are they captured asteroids (Higuchi & Ida, 2017), or were they formed via an impact of a larger body into Mars (Rosenblatt et al., 2016)? One of the limiting factors in addressing these questions is the lack of chemical composition information for these moons. The Japan Aerospace Exploration Agency is planning the Martian Moons eXploration (MMX) mission to answer this and other key questions regarding Phobos and Deimos (Kuramoto et al., 2018). MMX will accomplish its objectives by making comprehensive remote sensing measurements of Phobos and Deimos and then returning regolith samples of Phobos to Earth for detailed chemical analyses.

A key measurement objective of the MMX mission is to remotely determine the elemental composition of Phobos. One of the standard remote sensing techniques for measuring planetary elemental compositions

Table 1
MEGANE Science Goals, Objectives, and Measurements

MMX Objectives = MEGANE Science Goals	MEGANE Science Objectives	MEGANE Measurements
1. Determine whether Phobos is a captured asteroid or the result of a giant impact	1. Determine whether Phobos has a chondritic or achondritic (Mars-like) composition 2. Determine if Phobos' surface materials are depleted in volatile elements	Characterize the bulk concentrations of major, minor, and trace radioactive elements in Phobos' regolith Measure the K/Th ratio of Phobos' near-surface material Measure the H content of Phobos' regolith
2. Study surface processes on airless bodies in Mars orbit	3. Characterize variations in the elemental composition of Phobos' surface 4. Characterize horizontal (surface) and vertical (subsurface) variations in the H content of Phobos' near-surface (depth < 30 cm) materials	Make spatially resolved measurements of the Si, K, Fe, and Th content of Phobos' regolith Make spatially resolved measurements of H, Σ_a , and <A> on Phobos' surface Measure the H content and H layering in the top 30 cm of the regolith
3. Support the MMX Phobos sample-return objective	5. Assist with sample site selection 6. Document compositional context of returned samples	Provide rapid, spatially resolved assessment of the concentrations of H, Si, K, Fe, and Th, and the bulk composition parameters Σ_a and <A> on Phobos' surface

is planetary nuclear spectroscopy. This technique uses measurements of gamma-ray and neutron emissions from airless or nearly airless planetary surfaces to determine elemental concentrations within the top meter of the surface. The gamma rays and neutrons, most of which are generated by nuclear interactions initiated by galactic cosmic rays (GCRs), can be measured either from orbiting and/or landed spacecraft. Successful composition measurements have been carried out on a variety of planetary bodies, including the Moon, Mars, Mercury, Venus, and multiple asteroids (Boynnton et al., 2007; Feldman et al., 1998, 2002; Lawrence, Feldman, et al., 2013; Peplowski et al., 2011; Prettyman et al., 2006, 2012). The MMX mission will carry a gamma-ray and neutron spectrometer (GRNS) called Mars-moon Exploration with GAMMA rays and NEutrons (MEGANE). The MEGANE instrumentation is funded by NASA and is being designed and developed by The Johns Hopkins University Applied Physics Laboratory in collaboration with Lawrence Livermore National Laboratory.

The purpose of this paper is to describe the goals of the MEGANE science investigation as well as document the conceptual design of the MEGANE instrumentation. Section 2 describes the MEGANE science goals in the context of the MMX mission; section 3 describes the MEGANE instrumentation; section 4 describes the expected baseline and additional measurements that will be carried out by MEGANE instrumentation. Finally, section 5 describes the current status of the MEGANE development and summarizes the paper.

2. The MMX Mission and MEGANE Science Goals and Objectives

The MEGANE science investigation was designed to address MMX science goals related to Phobos surface composition measurements, as well as overall science goals for NASA planetary science investigations. The MMX mission goals and design are summarized by (Kuramoto et al., 2018). MMX has two primary science goals: 1) Reveal the origin of Mars' moons and gain a better understanding of planetary formation and material transport in the solar system; and 2) Observe processes that have affected the Mars system and Mars surface environment. MMX mission goals lead to four science objectives: 1) To determine whether the origin of Phobos is captured asteroid or giant impact; 2) to obtain a basic picture of surface processes acting on small airless bodies in orbit around Mars; 3) to gain new insight on Mars surface environment evolution; and 4) to better understand behavior of the Mars air-ground system and the water cycle dynamics. To accomplish its science goals and objectives, the MMX mission will carry out comprehensive remote sensing measurements aimed at understanding the geology, geophysics, and elemental composition of Mars' moons, as well as the environment around Mars. In addition to these remote sensing measurements, a primary objective of the mission is to collect and deliver to Earth 10 g or more of Phobos material for detailed characterization using Earth-based laboratory instrumentation.

Table 2
Phobos and Deimos Formation Theories

Origin hypothesis		Composition predicted	Expected MEGANE Compositional Measurements
Asteroid capture	Capture of organic- and volatile-rich outer solar system (D-type) body	Ultraprimitive (carbonaceous chondrite) composition, for example, the Tagish Lake meteorite (Brown et al., 2000)	Volatile-rich carbonaceous chondrites (e.g., Tagish Lake, CI, CM; Figure 1)
	Capture of organic and volatile-poor outer solar system (D-type) body	Carbonaceous chondrite composition with anhydrous silicates plus elemental C (Emery & Brown, 2004)	Volatile-poor carbonaceous chondrites (e.g., CR, CK, CO; Figure 1)
	Capture of inner solar system (S-type) body	Composition like common meteorites (e.g., ordinary chondrites) (Brearley & Jones, 1998)	Ordinary Chondrites (Figure 1)
In situ formation	Giant impact on Mars	Mixture of impactor and silicate-Mars-like materials (McSween et al., 2009)	Intermediate between Mars basaltic meteorites and impactor, with low K/Th (Figure 4)
	Coaccretion with Mars	Composition like bulk Mars	Ordinary chondrites with elemental ratios consistent with values derived for bulk Mars (Figure 3)

The MEGANE investigation has three science goals, two of which were adopted from MMX science objectives, with a third that supports the MMX Phobos sample acquisition and interpretation (Table 1). MEGANE science goals are 1) determine whether Phobos is a captured asteroid or the result of a giant impact; 2) study surface processes on airless bodies in Mars orbit; and 3) support the MMX Phobos sample-return objective. The science goals will be accomplished via science objectives, as detailed in Table 1.

2.1. MEGANE Science Goal 1: Determine Whether Phobos is a Captured Asteroid or the Result of a Giant Impact

Theories for Phobos' and Deimos' origins (Table 2) fall into two broad categories: gravitational/orbital capture of primitive solar system objects, and in situ formation near Mars. Capture hypotheses attempt to explain the characteristics that Phobos and Deimos share with C- and D-type asteroids, which have low densities, low albedo, and irregular shapes (Burns, 1978; Burns, 1992; Fraeman et al., 2012, 2014; Hartmann, 1990; Murchie & Erard, 1996; Pajola et al., 2013; Rivkin et al., 2002). Materials that can explain Phobos' D-type spectrum include both volatile-rich and volatile-poor lithologies, similar to primitive carbonaceous chondrite meteorites (Table 2). Solar system dynamical models, e.g., the "Nice model" (Gomes et al., 2005; Tsiganis et al., 2005), predict scattering of material from the outer to the inner solar system, providing a means for D-type bodies to reach the vicinity of Mars. Alternatively, Phobos and Deimos may be captured inner solar system (S-type) objects, which have been associated with ordinary chondrite materials (Nakamura et al., 2011; Peplowski, Bazell, et al., 2015; Yurimoto et al., 2011); however, this would require darkening and reddening, perhaps via space weathering, to match Phobos' D-type spectrum (Fraeman et al., 2012, 2014).

Phobos' and Deimos' near-circular, near-equatorial orbits are difficult to explain dynamically by capture, which typically results in objects with inclined, highly elliptical orbits. In situ formation models more easily predict the current orbits of Phobos and Deimos. In situ formation resulting from a giant impact on Mars follows from our understanding of the formation of Earth's moon. Here, a large impact produces a disk of materials from which Phobos and Deimos accreted (Craddock, 2011; Rosenblatt & Charnoz, 2012). The material is predicted to be composed of >50% devolatilized material derived from the impactor, with the remainder from Mars (Pignatale et al., 2018; Rosenblatt et al., 2016). Phobos and Deimos would spectrally resemble D-type bodies if a large amount of the material was from a D-type impactor, as the spectral properties of mixtures of bright and dark materials are dominated by the dark materials. However, the admixture would be depleted in volatile components due to heating during the impact event (Craddock, 2011; Hyodo et al., 2018; Nakajima & Canup, 2017), as opposed to the capture model, which would result in a nonvolatile depleted D-type composition. In situ formation by coaccretion with Mars (Safronov et al., 1986) predicts that Phobos and Deimos accreted from the same material that formed Mars, which has been modeled to be similar to ordinary chondritic materials (Wanke & Dreibus, 1988), though the bulk composition of any planet is necessarily model-dependent. However, this scenario could be distinguished from the capture of an inner solar system object via sample analysis of the returned MMX sample, as it predicts that Mars and Phobos would have similar isotopic ratios for oxygen and other elements, isotopic signatures that are highly diagnostic of Martian materials.

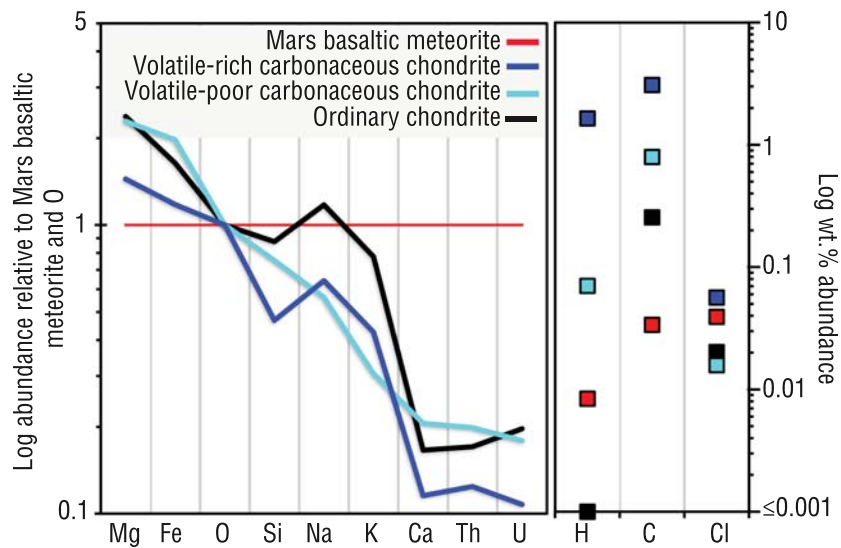


Figure 1. MEGANE's suite of elemental measurements provides multiple, redundant means to discriminate between Phobos origin hypotheses (Table 2). Curves and squares are reference compositions representing the mean class of materials. MEGANE's element-by-element precision (Table 4) is sufficient to differentiate between the four compositional groups. Data for the Mars basaltic meteorite compositions are compiled from McSween and Treiman (1998); data for the volatile-rich carbonaceous chondrite compositions are compiled from Kallemeyn and Wasson (1981) and Brown et al. (2000); data for the volatile-poor carbonaceous chondrite compositions are compiled from Kallemeyn and Wasson (1981); data for the ordinary chondrite compositions are compiled from Wasson and Kallemeyn (1988) and Brearley and Jones (1998).

The diversity of formation scenarios for Phobos and Deimos (Table 2) and the wide-ranging interpretations of the existing spectral reflectance data (e.g., Fraeman et al., 2012, 2014; Giuranna et al., 2011; Glotch et al., 2015; Yamamoto et al., 2018) illustrate a point: the origin of the Martian moons is an open issue for which spectral data are inconclusive and whose resolution requires knowledge of the elemental composition of the surface (Figure 1). To accomplish MEGANE science Goal 1, the MEGANE investigation will carry out two focused science objectives: 1) determine whether Phobos has a chondritic or achondritic (Mars-like) composition; and 2) determine if Phobos' surface materials are depleted in volatile elements.

2.1.1. MEGANE Science Objective 1: Determine Whether Phobos has a Chondritic or Achondritic (Mars-Like) Composition

MEGANE global-average values of H, O, Na, Mg, Si, K, Cl, Ca, Fe, Th, and U, derived from gamma-ray measurements, as well as H concentrations derived from neutron measurements, provide a robust dataset that can be used to discriminate between the Phobos and Deimos formation models (Figure 1). Thermal and epithermal neutrons also provide complementary information regarding Phobos' origin (Figure 2) (Elphic et al., 2016).

The diagnostic Fe/Si versus Fe/O ratio (Figure 3), which segregates materials according to chemical fractionation via differentiation, is one example of the use of MEGANE-derived element composition information to discriminate between chondritic (primitive) and achondritic (Mars-originating) compositions. Ordinary chondrites cluster at high Fe/Si versus Fe/O values due to the presence of both Fe-bearing silicates (Fe + Si + O) and FeNi metal (Fe). More volatile-rich carbonaceous chondrites are separated from the ordinary chondrites by greater O abundance, a result of containing higher abundances of clays, alteration minerals, and other volatile-rich phases. Volatile-depleted carbonaceous chondrites (higher Fe/O than volatile-rich carbonaceous chondrites) overlap with the ordinary chondrites, but are separated via Mg, Fe, H, and Cl measurements (Figure 1). Finally, achondritic material clusters at low Fe/Si versus Fe/O values, due to fractionation of FeNi metal to the core and core/mantle boundary during core formation (removal of Fe from the bulk) and the resulting formation of lithic crustal material (leftover Fe + Si + O), from which achondritic material is derived. Because Mars-originating exogenous material on Phobos is expected to be scarce (2–500 ppm) (Chappaz et al., 2013; Ramsley & Head, 2013), observation of chondritic versus achondritic material with MEGANE is diagnostic of Phobos' native composition, not later surface modification.

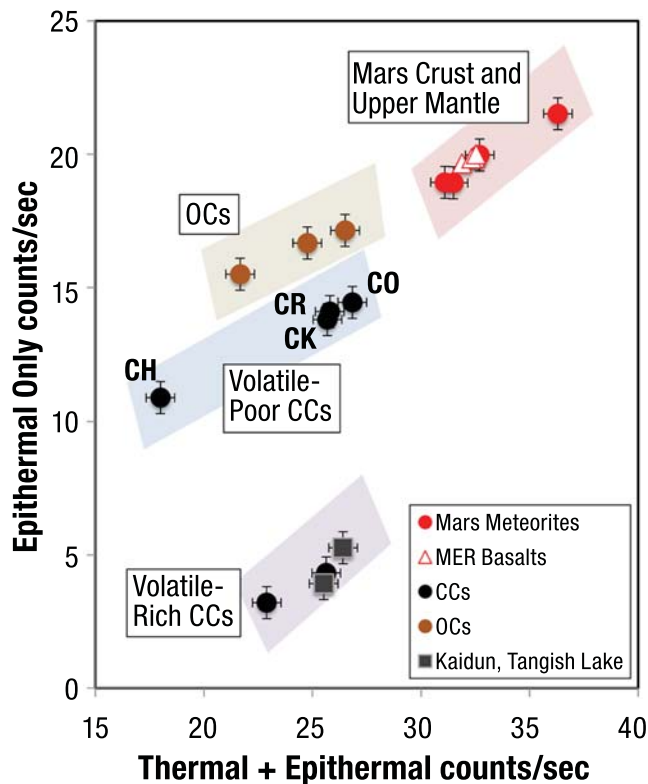


Figure 2. Breakdown of compositional end members (Figure 1) in neutron measurement space, showing that NS measurements also contribute to Phobos origin science (Elphic et al., 2016). Data points show simulated neutron count rates for a MEGANE-NS-type measurement with an eight-day measurement and a nominal orbit altitude (see Section 4). CC stands for carbonaceous chondrites; OC stands for ordinary chondrites.

(Murchie & Erard, 1996) is found on the remainder of Phobos' surface, as well as Deimos' entire surface. Here "red" and "blue" refer to the relative slope of the reflectance spectra, as both moons are dark and colorless in visible wavelengths.

The red and blue units may or may not be fundamental chemical units, as chemical and spectral units are not always correlated on planetary surfaces (e.g., Weider et al., 2015). On Mercury, much of the spectral reflectance variations are controlled by minor differences in graphite and is disconnected from variations in major element chemistry (Peplowski, Lawrence, et al., 2015). Phobos' spectral units have only subtle spectral features (Fraeman et al., 2012, 2014) to provide hints to the origin of their color difference. The red unit has absorption near 0.65 μm , attributed to Fe-phyllsilicates or a mixture of grain sizes of metallic Fe, which is lacking from the blue unit. Both units exhibit absorption due to OH near 2.8 μm , but the absorption is stronger in the red unit. This difference could be a signature of variable H content in the units, or alternatively, the blue unit may be enhanced in C, which would flatten its spectrum and subdue its mineralogic absorptions. Red and blue materials may be exogenous and endogenous materials, respectively. The blue unit is associated with Stickney ejecta, but not all ejecta are blue, suggesting that the blue unit may be exposed material from a subsurface reservoir of chemically distinct material (Basilevsky et al., 2014).

Due to Phobos' location in Mars' orbit, Phobos can accumulate material from Mars and Deimos. Impacts on Deimos will produce dust that will spiral into Mars, coating Phobos in the process (Horanyi, 2015). Similarly, Mars-originating material, lofted into orbit by Mars impactors, places dust in orbit (e.g., Andersson et al., 2015; Soter, 1971) that will coat Phobos; however, estimates are that just 2–500 ppm of Phobos' surface is Mars-originating material (Chappaz et al., 2013; Ramsley & Head, 2013). Space weathering (Hapke, 2001) results from the combination of meteorite and micrometeorite, solar wind, and high-energy particle bombardment, and for volatile-rich bodies, desiccation and alteration due to thermal processing. Space

2.1.2. MEGANE Science Objective 2: Determine if Phobos' Surface Materials are Depleted in Volatile Elements

Giant impact formation models of Phobos and Deimos predict surfaces depleted in highly and moderately volatile elements (Craddock, 2011; Hyodo et al., 2018; Nakajima & Canup, 2017), as heating during the event removes volatiles from the debris disk. Our Moon, whose giant impact origin is evident in its depletion of such volatiles relative to the Earth, is a good example of this type of process. One specific means of testing the giant impact hypotheses is K/Th measurements (Peplowski et al., 2011; Prettyman et al., 2015). MEGANE will provide robust measurements of K and Th, naturally radioactive elements that can be measured at trace amounts (~ppm to ppb). As incompatible lithophile elements, their ratio is generally preserved after melting and recrystallization. Because K is moderately volatile, whereas Th is refractory, K/Th decreases when a material is heated sufficiently in a chemically open system, that is, in a disk of ejected material after a giant impact. CI chondrites provide the primordial solar system K/Th ratio (~20,000; Figure 4). The terrestrial planets have moderate K/Th values (~3,000 to ~8,000), a consequence of volatile loss due to heating (solar and accretion). The Moon has the lowest K/Th value (~300), reflecting volatile loss during/after the Moon-forming giant impact. A chondritic K/Th value (~20,000) for Phobos supports captured asteroid and coaccretion hypotheses; a lower value supports the giant impact hypothesis.

2.2. MEGANE Science Goal 2: Study Surface Processes on Airless Bodies in Mars Orbit

Chemical variations on planetary surfaces offer insights into the processes that shaped those surfaces (Table 3). Phobos' surface, which is geologically diverse (Basilevsky et al., 2014; Veverka & Duxbury, 1977) shows evidence for compositional diversity via two distinct spectral units (Figure 5). The "blue unit" is located around Stickney crater, and the "red unit"

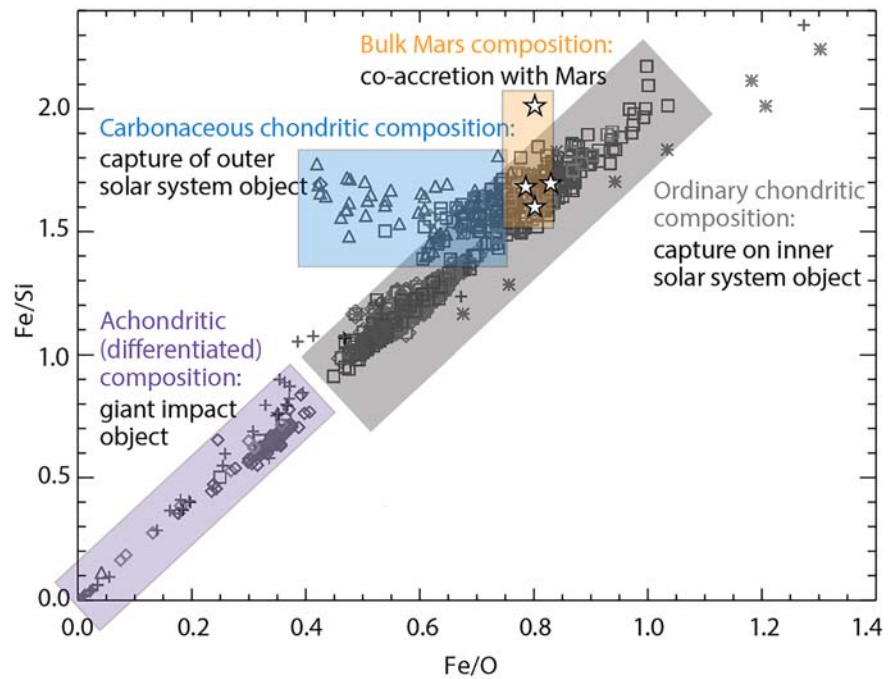


Figure 3. Fe/Si versus Fe/O measurements separate achondritic and chondritic meteorite groups, direct analogs to compositions predicted for each origin hypothesis. Color-coded values for each meteorite are plotted in Peplowski, Bazell, et al. (2015). The overlap of the carbonaceous chondrites with the ordinary chondrites can be separated via Mg, Fe, H, and Cl measurements.

weathering creates nanophase metallic Fe and Fe sulfides, which darken and redden the surface and obscure absorptions at visible to near-infrared wavelengths (Noble et al., 2001; Noguchi et al., 2011; Pieters et al., 2000). For C-rich bodies, formation of nanophase C may also be important (Trang et al., 2017). Mars' moons (1.5 AU) are located between the Moon (1 AU) and Vesta (2.4 AU), two well-studied objects that have played a large role in our understanding of space weathering. Phobos' surface compositions may be richer in C and volatiles than those bodies, so the relative importance of the various space weathering processes for the Martian moons is unknown.

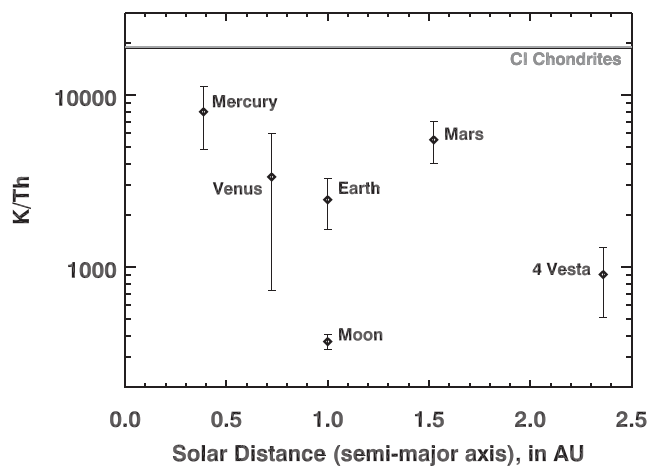


Figure 4. K/Th ratio for a number of planetary bodies versus solar distance, along with CI chondrites. The Moon's low K/Th ratio is believed to be due to its formation from a giant impact event.

MEGANE's science goal to study surface processes on airless bodies in Mars orbit is thus broad in scope, as it is inclusive of impact excavation processes, chemical processing, and space weathering. The two science objectives that address this science goal are 1) characterize variations in the elemental composition of Phobos' surface; and 2) characterize horizontal (surface) and vertical (subsurface) variations in the hydrogen content of Phobos' near-surface (depth < 30 cm) materials.

2.2.1. Science Objective 3: Characterize Variations in the Elemental Composition of Phobos' Surface

MEGANE elemental (H, Si, K, Fe, and Th) and neutron composition maps will characterize the compositional variability of Phobos' surface. Systematic differences in composition between the leading and trailing hemispheres would be evidence for the presence of exogenous material from Mars or Deimos (Horanyi, 2015). Correlations between elemental composition and spectral units would reveal underlying differences between the red and blue units. For instance, differences in the H content of the units have been invoked to explain their differences. MEGANE samples H content to depths of tens of cm, well below the upper few microns that is measured by reflectance spectroscopy. The upper centimeter has been repeatedly heated to 340 K in vacuum (Giuranna et al.,

Table 3
Range of Surface Processes Possibly Operating on Phobos

Surface process	Effects	Examples	Spatial compositional signature
Dust accumulation	Deimos-originating dust accumulates on Phobos as it spirals in toward Mars.	Models suggest rates of 1–5 kg/year, accumulating in a highly asymmetric distribution (Horanyi, 2015).	Longitudinal spatial variations that match the predicted Deimos dust accumulation model
Excavation of distinct subsurface materials	The red and blue units represent distinct compositions that are present in Phobos.	Geologic evidence that red and blue unit materials form large blocks comprising the interior of Phobos (Basilevsky et al., 2014)	Variations in the compositions of multiple elements that correspond with the red and blue units (Figure 6)
Space weathering	Exogenous, chondritic infalling material accumulates. Thermal modification depletes uppermost surface of volatile elements (Na and K).	Contamination of Vesta's basaltic equatorial regions with carbonaceous chondrite-like materials (Prettyman et al., 2012) S depletion on Eros (Kracher & Sears, 2005)	Comparison of MEGANE- and sample-derived elemental composition measurements, including end-member (achondritic, chondritic) admixing ratios and depth profiles as inferred from MEGANE and sample acquisition depth

2011; Kuhrt & Giese, 1989) due to diurnal illumination, which would have removed all but the most tightly bonded H species. Thus, knowledge of subsurface volatile content is essential for characterizing Phobos' native volatile content and its heterogeneity among Phobos' red and blue units.

Neutron-derived composition parameters will also be used to characterize elemental abundance variations across Phobos' surface. Macroscopic thermal neutron absorption, Σ_a , which is sensitive to variations in elements with large or small neutron capture cross sections, has been used to derive compositional information on the Moon (Elphic et al., 2000; Feldman et al., 2000; Peplowski, Klima, et al., 2016), Vesta (Prettyman et al., 2013), and Mercury (Peplowski, Beck, & Lawrence, 2016). On Mercury, Σ_a , Fe, and albedo data were used to infer C concentrations (Peplowski, Klima, et al., 2016). Carbon concentrations could be similarly derived on Phobos, thus providing additional information toward meeting the science objectives (Figure 1). Fast neutrons measure average atomic mass, $\langle A \rangle$ (Gasnault et al., 2001), which supplies additional constraints on elemental variations (e.g., Lawrence et al., 2017).

2.2.2. Science Objective 4: Characterize the Surface and Subsurface Volatile Content of Phobos' Near-Surface (Depth < 30 cm) Materials

The MMX mission will use Phobos' elemental composition as a window from which to understand volatile delivery to the inner solar system. This objective requires the acquisition of a pristine sample of Phobos' surface material, particularly with respect to its H content. For airless solar system objects, the upper

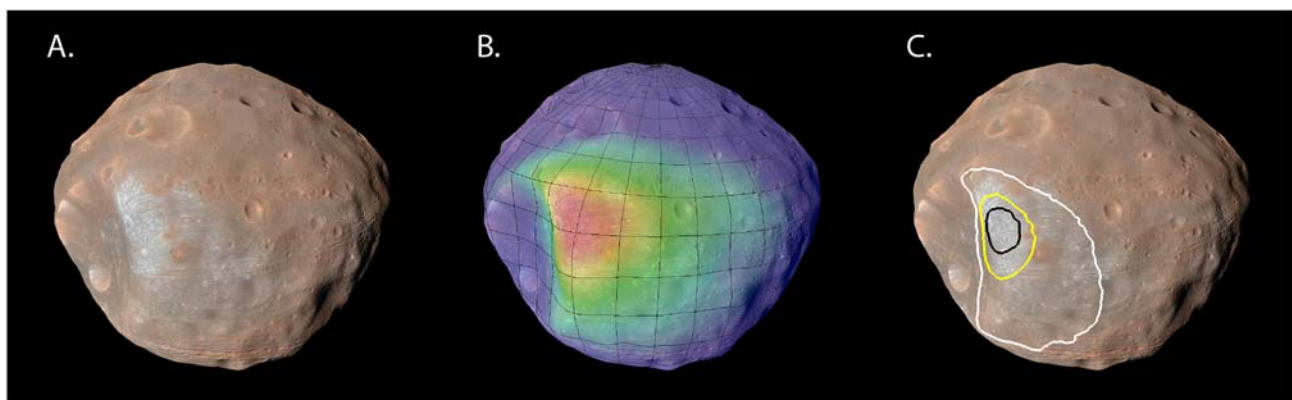


Figure 5. (A) High Resolution Imaging Science Experiment Phobos color map (based on data from Thomas et al., 2011), showing the blue and red spectral units, projected onto a Phobos shape model using the Applied Physics Laboratory's Small Body Mapping Tool (Ernst et al., 2018). (B) MEGANE's spatial footprint at an altitude of one-Phobos radius, with the colors corresponding to the fractional contribution each surface location yields to the MEGANE signal. At one-body radius, MEGANE's footprint enables a measurement dominated by Phobos' blue unit. (C) MEGANE footprints at lower altitudes, such as may be achieved during MMX descent operations. Lower altitudes enable MEGANE to measure more localized areas and also increase the strength of the surface signals.

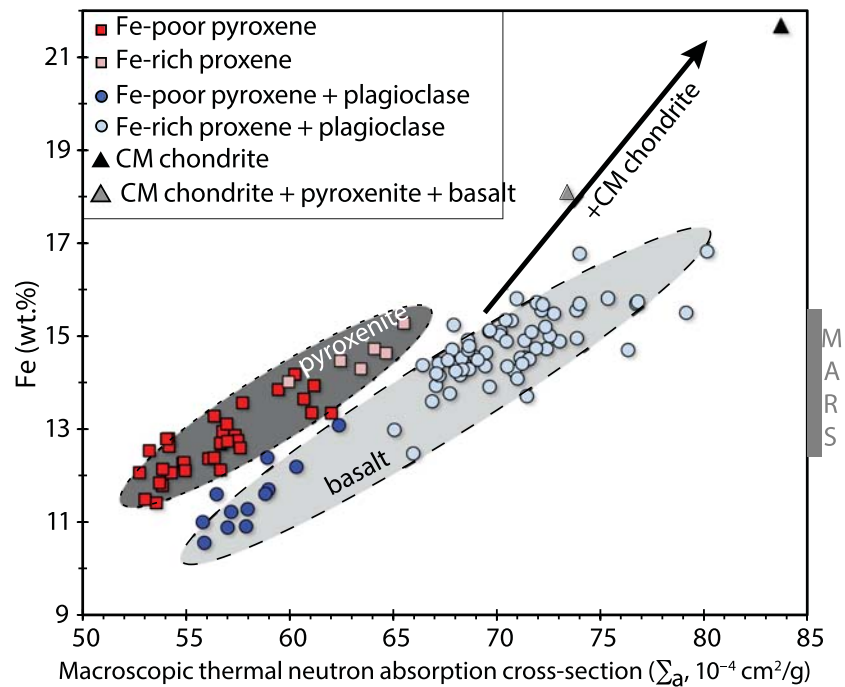


Figure 6. MEGANE measurements provide a basis for mapping petrologic (rock) types on Phobos, important data during sample site selection. Igneous rocks and carbonaceous chondrites are clearly distinct in Fe versus Σ_a space. Data from (Beck et al., 2015). The “MARS” Fe value is from the shergottite, nakhlite, and ALHA84001 meteorites.

centimeters of the surface are subject to chemical alteration (e.g., Peplowski, Bazell, et al., 2015, and references therein). The MMX mission seeks to avoid this issue by acquiring a sample from a depth of >2 cm. MEGANE neutron data provide a means to confirm that the returned sample of Phobos is representative of the near subsurface, as neutron data measure H content, including discriminating between upper and lower layers with differing H content to a depth of ~ 30 cm (Lawrence et al., 2006; Lawrence, Feldman, et al., 2013; Maurice et al., 2011).

2.3. MEGANE Science Goal 3: Support the Phobos Sample-Return Objective

MMX will return a ~ 10 -g sample of Phobos to Earth for detailed geochemical study. Phobos' spectral (and perhaps compositional) properties vary at all spatial scales observed to date (e.g., Figure 5). Thus, MEGANE seeks to provide chemical context for the returned sample in order to understand how the sample, collected at the $\sim \text{cm}^2$ scale, relates to Phobos' ($1,500\text{-km}^2$ surface area) global compositional variations. Additionally, spatially resolved measurements of variations in the elemental composition and neutron compositional parameters of Phobos' surface will inform the selection of sampling site(s) and provide a reference for comparison to the laboratory analysis of the sample. Together, remote sensing and sample analysis constrain Phobos' mean (global) and regional surface composition, providing a comprehensive view of Phobos' surface. Weathering and other secondary processes that modified surface materials (e.g., heating, aqueous alteration) (Nakamura et al., 2011) can be identified via sample analysis; elemental maps can constrain how widespread those processes are. The two science objectives that will accomplish this goal are 1) inform and assist with sample site selection and 2) document the compositional context of the returned samples.

2.3.1. Science Objective 5: Inform and Assist With Sample Site Selection

The primary goal of the MMX mission is to return a sample of Phobos to Earth for detailed study. Sample site selection is therefore a crucial component of the MMX mission. Site selection requires a synthesis of all MMX remote observations. MEGANE provides maps of H, Si, K, Fe, and Th, along with the neutron macroscopic absorption cross section Σ_a and average atomic mass $\langle A \rangle$. These parameters resolve petrologic variance (e.g., Beck et al., 2015, 2017; Usui et al., 2010; Usui & Iwamori, 2013; Usui & McSween, 2007), including Mars-like mafic (basalts) from ultramafic (pyroxenite) rocks and each from admixtures containing various amounts of carbonaceous chondrite materials (Figure 6). MEGANE composition maps for the red

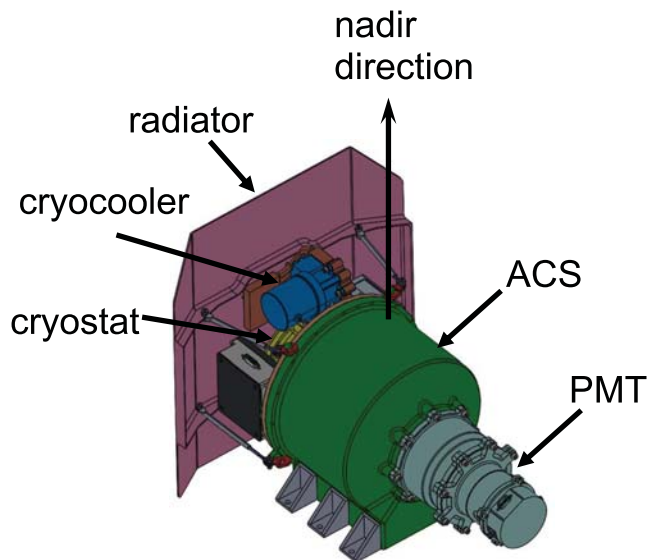


Figure 7. Drawing of the MEGANE gamma-ray spectrometer (GRS). The components seen from the outside are labeled; the Ge crystal is located within the cryostat. The radiator is a notional design. The nadir direction viewing Phobos is through the side of the ACS. The length of the GRS from the end of the PMT to the radiator is ~ 30 cm.

and blue spectral units can be combined with higher-resolution spectral unit maps to develop inter-instrument criteria for sample site selection. This is particularly important if MEGANE observations indicate compositional differences between the red and blue units, for instance in volatile content or major element chemistry. Such information may reveal that one of the two units is less processed material and therefore a better choice for understanding the native composition of Phobos.

2.3.2. Science Objective 6: Document the Compositional Context of the Returned Samples

Laboratory analysis of the Phobos samples will provide the most robust constraints on Phobos' origin. The question of sample representativeness is fundamental. MEGANE measurements form the basis for evaluating how well the sample represents Phobos' mean, regional, and subsurface (depths of up to ~ 30 cm) composition. MEGANE's measurement of H depth variability can reveal how volatile element content varies at a depth well below the maximum depth reached by the sample acquisition system. Volatile depletion in the uppermost material on exposed objects (e.g., asteroid 433 Eros) (Kracher & Sears, 2005) is a known phenomenon that alters the chemistry of surface materials relative to their original compositions. Depletion of H in the uppermost surface is likely, given the diurnal thermal wave penetrates roughly 1 cm (Kuhrt & Giese, 1989). MEGANE samples elemental composition to a depth of ~ 30 cm; therefore, MEGANE volatile element (H, Na, and K) measurements, combined with analysis of the returned sample (~ 2 – 10 cm), allows reconstruction of how

space weathering has affected chemistry of Phobos' regolith, which provides crucial context for efforts to reconstruct the moon's evolution.

3. MEGANE Instrumentation

The MEGANE instrumentation combines a high-purity Ge (HPGe) gamma-ray spectrometer (GRS), a ^3He -sensor based NS, and a shared Data Processing Unit (DPU). The GRS measures gamma rays with energies between 100 keV and 10 MeV to characterize the abundances of key elements in near-surface materials. The NS measures neutron fluxes in three broad ranges, from thermal (<0.2 eV) to fast (>0.5 MeV) energies, to map the distribution of H and bulk chemical properties of the surface. Together, the GRS and NS provide orbital reconnaissance data that can address MMX science goals, inform the selection of MMX sample sites, and document the geochemical context of the returned sample.

3.1. MEGANE Gamma-Ray Spectrometer

The MEGANE GRS (Figure 7) is based on heritage from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission (Goldsten et al., 2007), with improvements based on lessons learned from MESSENGER that were validated with a prototype GRS known as GeMini Plus (Burks et al., 2018) built for a NASA instrument development program. Those improvements are also being incorporated into the GRS for NASA's Psyche mission (Lawrence et al., 2019), which also provides design heritage for MEGANE. As with MESSENGER, the MEGANE GRS uses a 5-cm-diameter by 5-cm-long coaxial Ge crystal that is encapsulated within an Al enclosure and then suspended by low conductivity supports within a vacuum cryostat that provides thermal isolation from the surrounding environment. The cryostat is surrounded by a borated plastic scintillator anticoincidence shield (ACS), which is read out by a photomultiplier tube (PMT) identical to that used for MESSENGER. The scintillator has a thickness of 1.8 cm for its cylindrical portion, and it tapers to a thickness of 4.92 cm at the bottom near the PMT. The ACS serves two purposes. First, it actively rejects charged particle background within the Ge crystal. Second, because it contains 5% boron by weight, it also serves as a fast-neutron detector by detecting neutrons that interact in the scintillator via the $^{10}\text{B}(n, \alpha)$ reaction. This type of scintillator is used widely for detecting planetary fast neutrons (e.g., Lawrence, Peplowski, et al., 2013; Lawrence, Feldman, et al., 2013; Maurice et al., 2000, 2011). The MEGANE GRS gamma-ray sensor operates at a temperature of 90 K, which

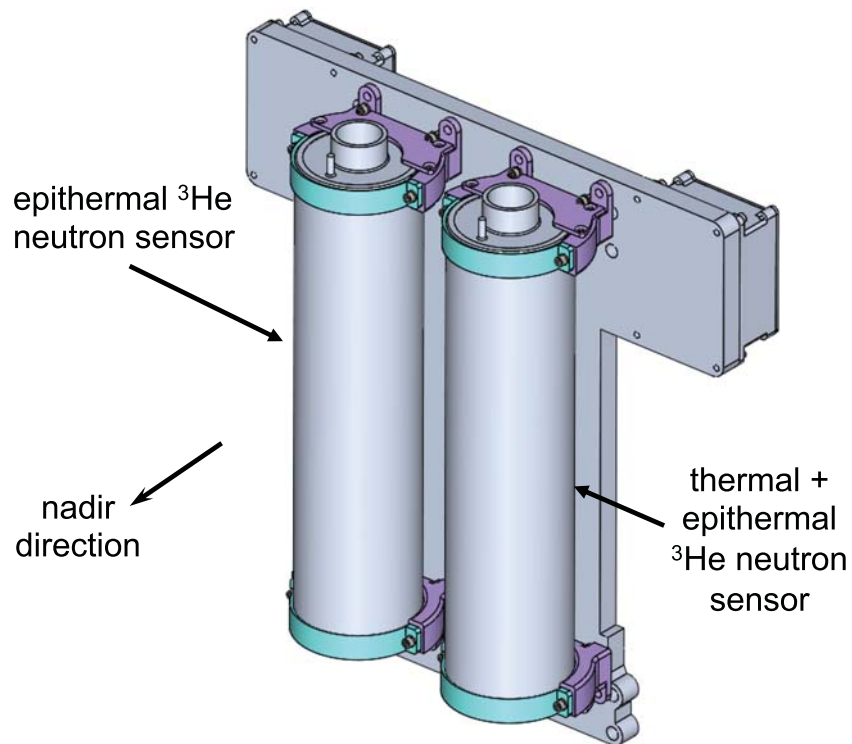


Figure 8. MEGANE neutron spectrometer with two ³He neutron sensors. The nadir direction viewing Phobos is perpendicular to the cylinder axes of the sensors. The epithermal sensor uses the Cd covering. The length of each sensor assembly is ~30 cm.

is achieved with a Ricor K508N cryocooler. This cooler is an adaptation of the K508 used for MESSENGER. Modifications from the MESSENGER GRS, based on lessons learned from operations around Mercury (Evans et al., 2017), include 1) a vent-to-space encapsulation for the Ge sensor to reduce contamination build up from annealing operations; 2) higher temperature anneals to better mitigate radiation damage from solar and GCRs (Peplowski et al., 2019); and 3) reading and processing the Ge signals using all-digital electronics.

3.2. MEGANE Neutron Spectrometer

The MEGANE NS (Figure 8) uses the same type of ³He gas proportional sensors (5-cm diameter by 20-cm long) as the successful Lunar Prospector NS (Feldman et al., 2004). However, instead of mounting the sensors end-to-end as was done for Lunar Prospector, for MEGANE they will be mounted in parallel, which provides substantial mass savings. Based on neutron transport models of their response, it was determined that cross talk and shadowing can be minimized when the tubes are separated by at least one tube radius. The NS incorporates two identical ³He sensors – one covered in 0.5 mm of thermal-neutron-absorbing Cd and the other bare – to detect neutrons (*n*) from Phobos via the ³He + *n* capture reaction. The bare tube allows neutrons with all energies to pass into the ³He sensor, thereby providing measurements of thermal (neutron energy $E_n < 0.4$ eV) and epithermal (0.4 eV $< E_n < 100$ keV) neutron fluxes. The Cd covering on the other tube stops thermal neutrons from entering the ³He sensor, rendering it an epithermal-neutron-only sensor. The thermal neutron count rate is derived from the difference in the two counting rates. ³He sensors are commercial off-the-shelf units from Baker Hughes (originally General Electric Reuter Stokes). They exhibit high sensitivity to neutrons and low sensitivity to background, are extremely rugged and radiation tolerant, and have extensive spaceflight heritage on national security and NASA missions (Feldman et al., 2004; Hahn et al., 2003). As with the GRS sensor, the MEGANE NS benefits from the Psyche GRNS design heritage (Lawrence et al., 2019).

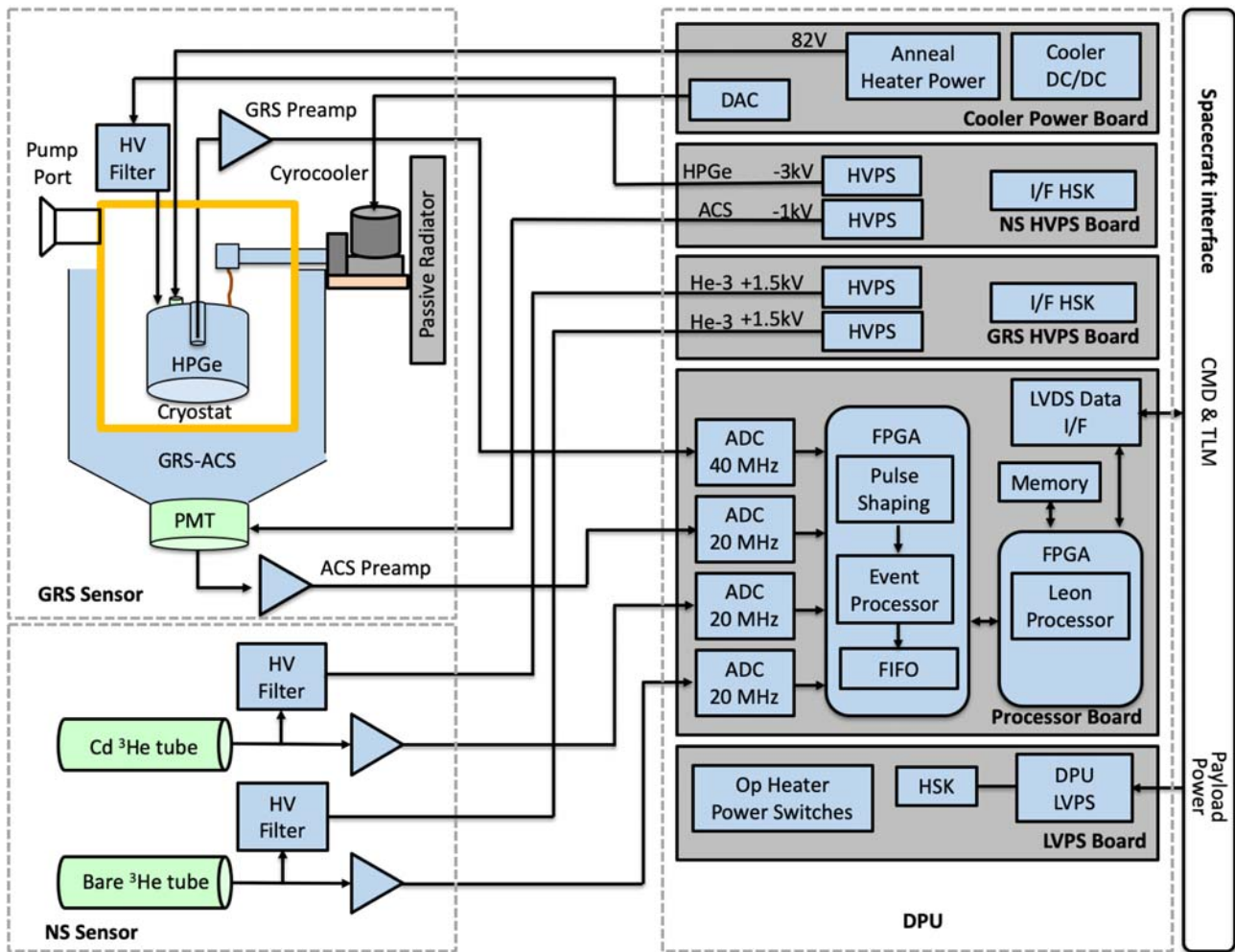


Figure 9. MEGANE block diagram.

3.3. Data Processing Unit

A simplified block diagram of the MEGANE electronics is shown in Figure 9. MEGANE uses a single DPU to service both the GRS and NS sensors. The DPU provides power, command and control, health and status monitoring, data processing, and formatting functions for each of the four detectors (HPGe, ACS, and two NS sensors). It contains five board “slices,” functionally identical to those in the MESSENGER GRS DPU: a processor board, a low-voltage power supply (LVPS) board, GRS and NS high-voltage power supply (HVPS) boards, and a cryocooler control board.

4. Expected MEGANE Measurements

Successful gamma-ray and neutron measurement investigations require extended periods of time (≥ 10 s of hours) at altitudes of ≤ 1 -body radius (Peplowski, 2016). While a detailed MMX mission plan is still in the formulation stage, the notional MMX plan will utilize low-altitude quasi-satellite orbits (LA-QSO), which provide equatorial coverage across Phobos (Scheeres et al., 2019). For the purpose of determining sensitivities to elemental concentrations, we use 10 days (240 hr) of total accumulated time at altitudes less than one-Phobos radius and we adopt these criteria, unless otherwise noted, for all performance estimates.

4.1. Expected GRS Measurements

Table 4 lists the primary gamma-ray lines used to make elemental composition measurements, along with the abundance sensitivities and precisions needed to meet the MEGANE science objectives. Calculations that estimate the GRS measurement performance were carried out using a combination of measured

Table 4
List of Primary Gamma-Ray Lines used to Make Elemental Composition Measurements, Along with Required Detection Thresholds and Precisions Needed to Discriminate Between the Formation Models (see Figure 1)

	Peak (keV)	Detection threshold	Relative precision
H ^a	2223.2	100 ppm	20%
O ^a	6128.6	20 wt. %	33%
Na	439.4	2 wt. %	30%
Mg ^a	1368.6	2 wt. %	33%
Si ^a	1779.0	2 wt. %	20%
K ^a	1460.8	300 ppm	20%
Cl	1957.6	0.15 wt. %	25%
Ca ^a	1942.7	5 wt. %	33%
Fe ^a	846.9	1.5 wt. %	20%
	7631.1		
	7645.5		
Th ^a	2614.5	150 ppb	20%
U	351.9	50 ppb	90%
	609.1		

^aRequired to meet MEGANE's Level 1 requirements.

MESSENGER GRS data and particle transport simulations. These calculations assumed identical energy resolution performance as the MESSENGER GRS at Mercury arrival (5 keV at 1,333 keV), which was degraded relative to postlaunch performance following the 6.6-year cruise to Mercury due to accumulation of radiation damage (Evans et al., 2017). Since MMX cruise is only 1 year, and our instrument development efforts have generated procedures that fully recover radiation damage (Peplowski et al., 2019), MEGANE performance at Phobos is expected to exceed MESSENGER GRS. MESSENGER GRS flight-measured spacecraft backgrounds were adopted as the MEGANE backgrounds, as both instruments are spacecraft-mounted, and the MMX fuel mass during LA-QSO will likely be comparable to that during MESSENGER Mercury flybys.

Gamma-ray simulations (see Peplowski, 2016), were carried out (Figure 10) for two compositions – a Mars-like material and a volatile-rich carbonaceous chondrite material (Figure 1). The simulations combined three inputs to produce model gamma-ray spectra. Modeled gamma-ray spectra for all compositions were produced using the particle transport code Monte Carlo N-Particle eXtended (Pelowitz, 2005). Those spectra were convolved with the MESSENGER GRS detector response function to incorporate the energy-dependent gamma-ray detection efficiency and system energy resolution. The MESSENGER GRS response, which

includes the intrinsic detection efficiency as well as attenuation losses in the instrument housing, is appropriate as it has an identically sized HPGe sensor as MEGANE. The use of response-convolved models and benchmarking to in-flight measurements is detailed in Peplowski (2016), who applied this technique to Near-Earth Asteroid Rendezvous (NEAR) GRS measurements of asteroid 433 Eros. The CI chondrite composition was adopted from Lodders and Fegley (1998). The Mars composition is a crustal composition derived from in situ and remote sensing observations. The Mars and carbonaceous chondrite simulations, benchmarked to MESSENGER flight data, demonstrate large and easily characterized signatures for our elements of interest. The Mercury benchmark, a comparison of MESSENGER GRS data acquired at one-body radius to a modeled gamma-ray spectrum for mean Mercury composition, provided a flight-data-verified normalization for all simulations. Comparisons of modeled and measured spectra reveal a model accuracy of >85% (absolute count rates) (Peplowski, 2016). The statistics are based on a 10-day accumulation at one-body-radius altitude, and full-body bulk compositions for all the elements listed in Table 4 will be obtained within these 10 days of accumulations, thus meeting the MEGANE measurement requirements.

GRS measurements will have sufficient statistical precision to map the elemental compositions of Si, K, Fe, and Th across Phobos' surface. Figure 5b shows the instantaneous GRS footprint of measurements at an altitude of one-Phobos radius. Figure 5a shows multispectral imaging data and the location of the blue unit near Stickney crater. As seen, GRS measurements are spatially resolved at the scale of the blue unit, enabling MEGANE to identify differences in the elemental composition of the red and blue units. Figure 11a shows the expected GRS coverage for currently planned LA-QSO orbits, which indicates there is sufficient coverage for altitudes less than one-body radius to obtain robust gamma-ray measurements both over the blue-unit regions (longitudes 330–30°) and red-unit regions antipodal to the blue unit (150–240°).

4.2. Expected Measurements: NS

The Monte Carlo N-Particle (MCNP) code (Goorley, 2013) was used to calculate the flux of low-energy neutrons at Phobos' surface as generated via interactions from an average GCR spectrum. The neutron flux was modeled for dozens of compositions, ranging from primitive meteorites (i.e., Tagish Lake), ordinary chondrites, to differentiated Mars materials. Using a two-degree resolution Phobos shape model, we calculate the contribution of each visible facet to the flux arriving at the NS, from which a position-dependent NS count rate was derived. Useful neutron data can be obtained at higher altitudes than gamma-ray data, so we used altitudes of ≤ 1.5 -body radius in the analysis and a notional Phobos LA-QSO. We test the ability of NS data to resolve the blue versus red unit by assigning each spatial unit a different composition, and

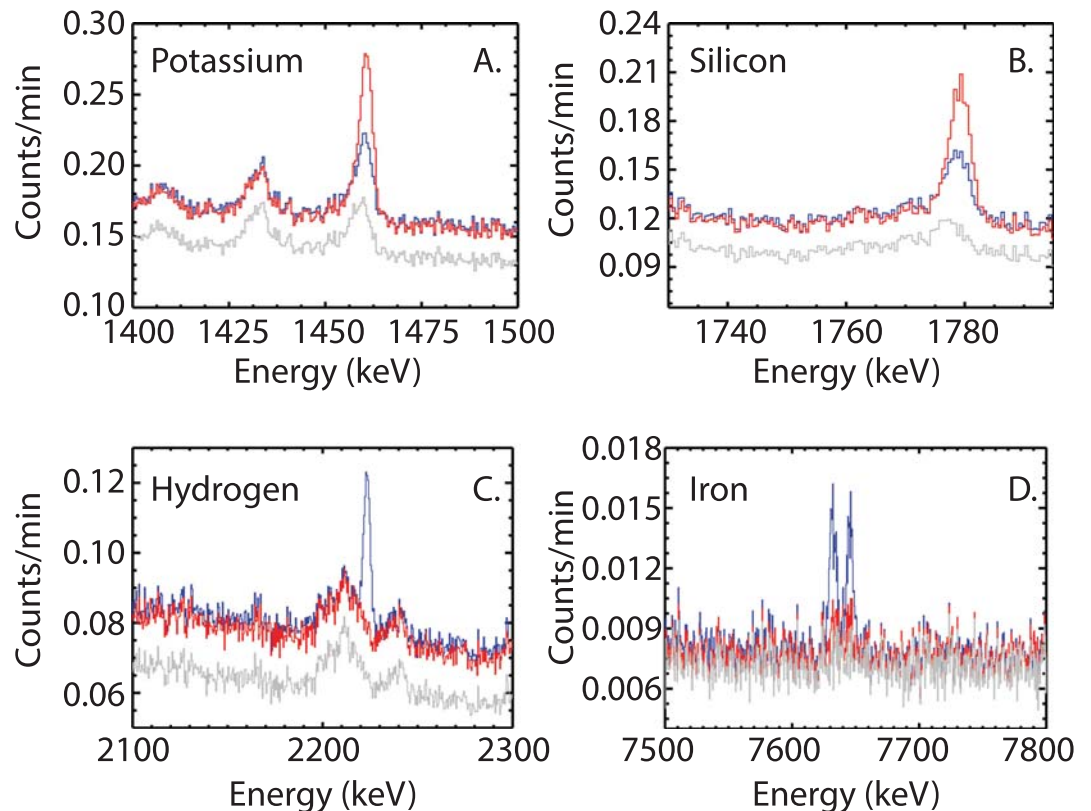


Figure 10. Simulated gamma-ray spectra for different elemental gamma-ray lines and Phobosformation hypotheses. For each panel, the blue traces show compositions expected for capture of a primitive asteroid (CI chondrite-like composition), and the red traces show compositions associated with a giant impact (Mars-like composition). MESSENGER-measured backgrounds are the light gray traces. These simulated gamma-ray spectra use an altitude of one-body radii and are benchmarked to flight data from the MESSENGER GRS. Comparisons of modeled and measured spectra for prior measurements at the asteroid Eros reveal a model accuracy of >85% (absolute count rates) (Peplowski, 2016). Statistics are based on a 10-day measurement at one-body-radius altitude.

deriving separate count rates from each unit (Figure 12). Neutron backgrounds from Mars and GCRs are determined based on extrapolated Mars Odyssey data to Phobos' orbit (Feldman et al., 2002), with responses adjusted for different sensors. We assume a spacecraft background of 2 cps for both ^3He sensors (Maurice et al., 2004). During MESSENGER cruise, no thermal neutrons and ~ 2 cps fast neutrons were measured, which bounds these background assumptions. Fast neutron count rates, obtained with the GRS ACS, are derived on the basis of MESSENGER fast neutron data (Lawrence et al., 2017), as the MESSENGER and MEGANE fast-neutron detectors are the same type of scintillator, and similar sized. Figure 11b shows that NS measurements have sufficient coverage to distinguish compositional differences between the red and blue units, if such differences are present.

4.3. Possible Measurements of Opportunity

The primary measurements that will satisfy the MEGANE science objectives will be obtained during the LA-QSO. However, the MMX spacecraft will carry out multiple descent and landing operations at Phobos in order to practice and then execute its sample-collection activities. Such operations provide an opportunity for very low-altitude MEGANE measurements. In addition, the MMX spacecraft is planning to carry out multiple flyby maneuvers at Deimos. If these Deimos flybys are at low enough altitudes, then MEGANE measurements might also be made at Deimos. The possibility of making useful MEGANE measurements in both these scenarios is described here.

4.3.1. Landing, Descent, and Surface Measurements at Phobos

It is expected that each of the Phobos descent and landing sequences will last multiple hours, wherein the MMX spacecraft will be at altitudes much lower than one-Phobos radius. Additionally, the MMX

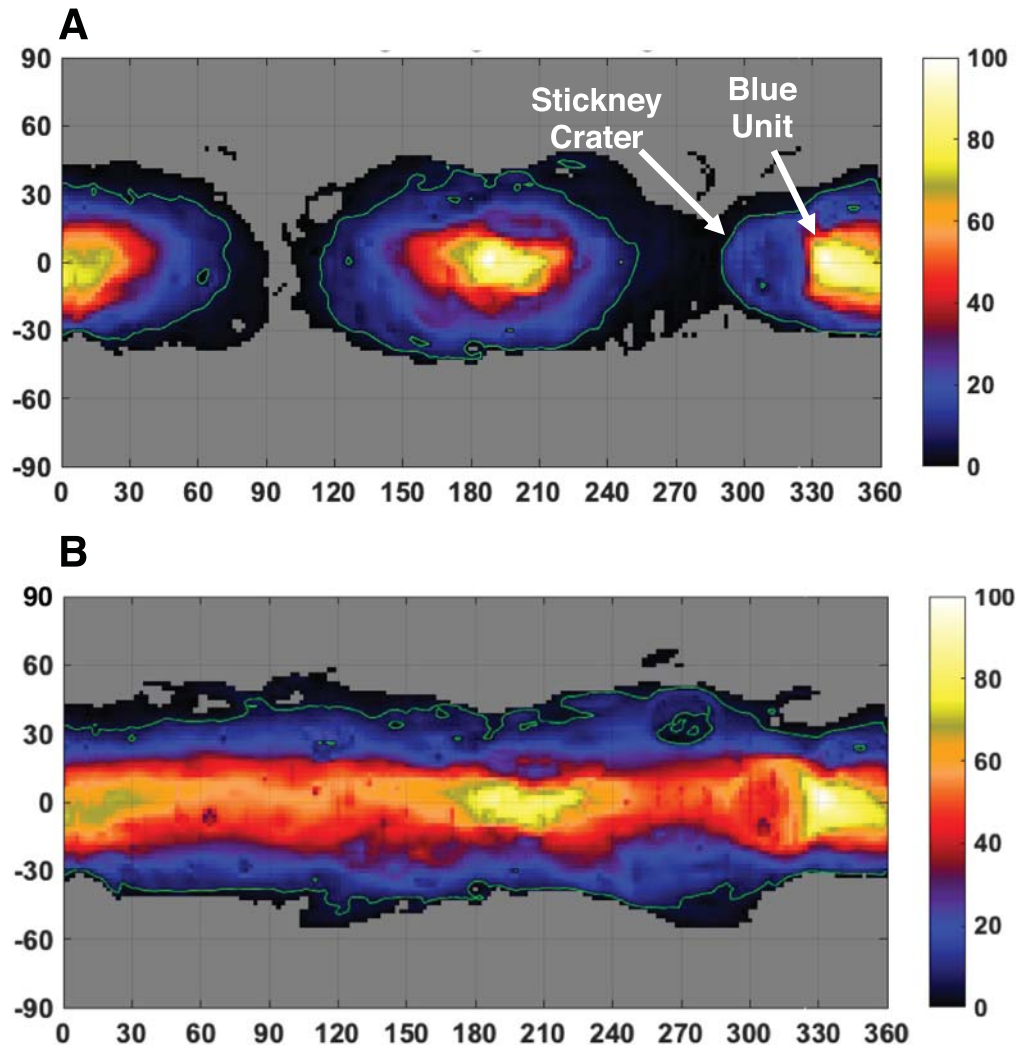


Figure 11. (a) GRS coverage over Phobos' surface for altitudes less than one-Phobos radius. Outlines represent areas where the percentage coverage contribution (relative to the maximum) is greater than 5%. The variable altitude coverage is due to Phobos' nonspherical shape. (b) NS coverage over Phobos' surface for all LA-QSO altitudes. Outlines represent areas where the percentage coverage contribution (relative to the maximum) is greater than 5%.

spacecraft will spend ~ 2.5 hours on the surface during sample collection(s). While the sample-collection activities and spacecraft health and safety take the highest priority, operation of the MEGANE instruments during even some portion of descent, landing, and surface operations would be highly valuable. Landed gamma-ray data from the NEAR mission, which acquired data for 14 days on the surface of asteroid 433 Eros, provide a key demonstration of the value of such landed data (Evans et al., 2001; Peplowski, Bazell, et al., 2015). The two improvements to MEGANE measurements, relative to LA-QSO measurements, are a significantly higher signal-to-background, and significantly smaller spatial footprint. Here we describe the quantitative improvements that could be obtained for a single descent and landing operation.

A mission profile for descent and landing is not yet designed, but preliminary sequences consist of an initial descent phase of 3–4 hr from altitudes of 20–30 km to 2–3 km; and a further phase from 2–3-km to 100-m altitude could last ~ 30 min. Such a sequence would last approximately 4–4.5 hours. At landing, the MMX spacecraft would spend approximately 2.5 hr on the surface. To gain an understanding of the quality of data that could be obtained when operating during such a descent and landing sequence, simulated gamma-ray spectra were generated and compared to the spectra that would be obtained during nominal LA-QSO operations at an altitude of one-Phobos radius (Figure 13). While the overall statistical precision of the LA-QSO

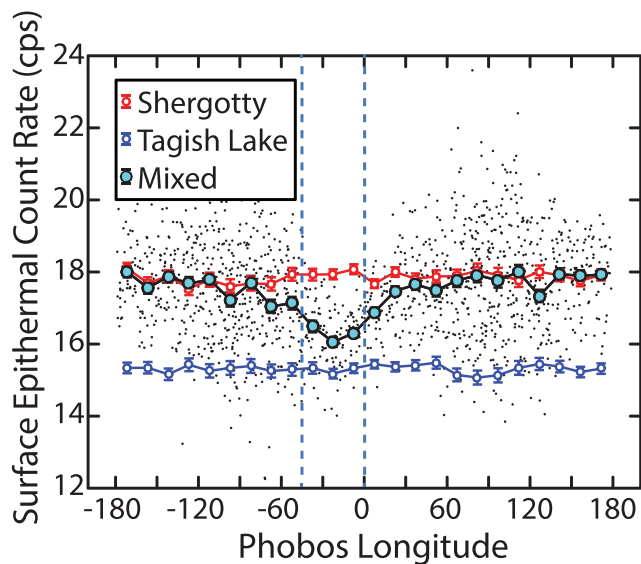


Figure 12. Neutron measurement traces for two end-member compositions—the Tagish Lake carbonaceous chondrite and the Shergotty Mars meteorite. Three surface compositions are examined, including Phobos as pure Tagish Lake (blue) and pure Shergotty (red), as well as Tagish Lake in the blue unit (dashed lines) and Shergotty otherwise (teal). Error bars are included for an 8-day measurement at ≤ 1.5 body altitude.

data are better than estimated descent and landing data, the descent and landing data have ~ 4.5 times better signal-to-background than the LA-QSO. In particular, good precision measurements could be made of Mg, Fe, and Si (Figure 13b), as well as K (not shown). A similar quality measurement could be obtained from the landing site during ~ 2.5 hours of data collection. Neutron data (also not shown) would enable a statistical precision of $\sim 1\%$ or less for H measurements during every 15 min of data collection.

In regards to spatial footprint, Figure 5c shows the improvement gained as the altitude is lowered from the nominal one-Phobos-radius to the altitudes obtained during descent and landing. The order-of-magnitude improvement in spatial resolution would result in a corresponding improved compositional context for any returned samples.

4.3.2. Operation During Deimos Flybys

While the primary focus of the MMX mission is to make comprehensive measurements of Phobos, the MMX spacecraft is planning to make a number of Deimos flybys aimed at performing science observations with the MMX remote sensing payload. In regards to composition, a key question is to understand if Phobos and Deimos have a similar or different bulk composition. Sufficient gamma-ray data require multiple hours of accumulation at altitudes closer than one-body radius, a condition that will not be met during Deimos flybys. Neutron measurements have a higher count rate, and therefore require less accumulation time and can be obtained from somewhat higher altitudes. While not element

specific, neutron data from Deimos could be directly compared to Phobos neutron data to answer the question if their compositions are similar or different (e.g., Figure 2; see also (Elphic et al., 2016)). Characterization of Deimos' composition through low-energy neutrons during flybys ultimately depends on gathering a statistically significant estimate of the neutron leakage flux signal in the presence of background. More flybys, smaller closest-approach distances, and slower flyby speeds all provide more

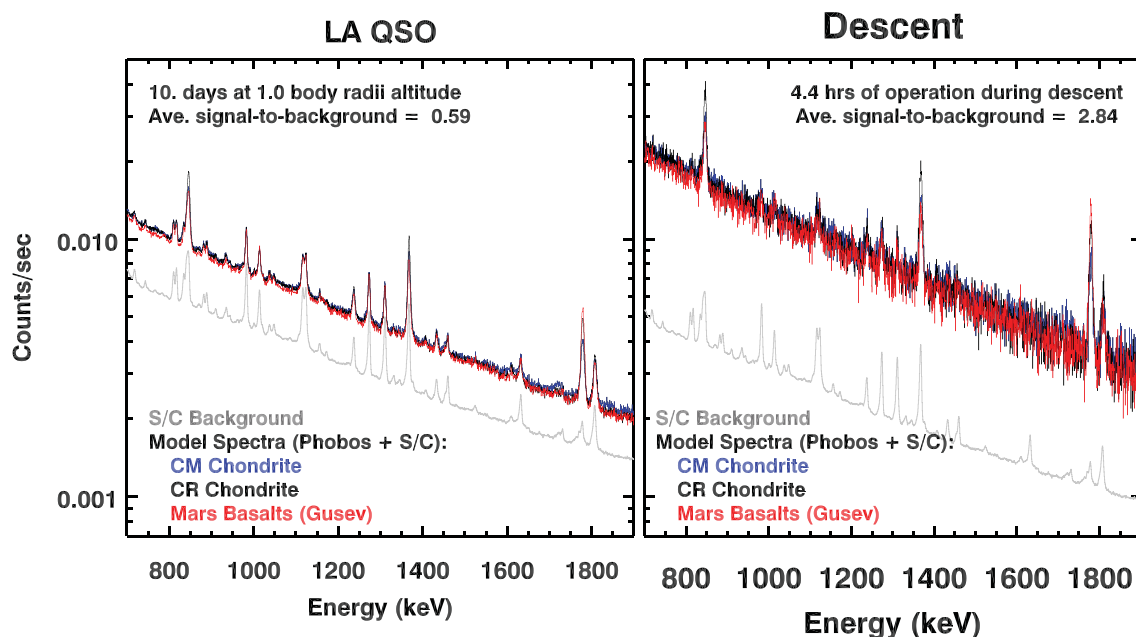


Figure 13. Simulated gamma-ray spectra for (a) 10 days of accumulation time at 1-Phobos radius altitude; and (b) 4.4 hr of accumulation during altitudes ranging from 0 to 2.5 km, such as may be experienced during descent to the surface of Phobos. Black, red, and blue traces show expected spectra from CR chondrite, Mars basalts, and CM chondrite, respectively. Gray traces show expected background spectra.

Table 5
Neutron Detection Significance for Five Identical Flybys at Various Deimos Closest-Approach Altitudes

Closest-approach altitude (km)	$\Delta C_{\text{therm} + \text{epi}} / \sigma_{\text{therm} + \text{epi}}$	$\Delta C_{\text{epi}} / \sigma_{\text{epi}}$
10	2.12	3.81
20	1.25	2.20
50	0.48	0.83
100	0.18	0.32

neutron counts from the moon. Yet, even a large number of distant flybys cannot overcome the effects of background and limited Poisson statistics. Given MMX trajectory uncertainties and mission safety constraints, a key determination will be an acceptable closest-approach distance. We examined the effects of five identical flybys, at 1 km/sec, for 10, 20, 50, and 100-km closest approach altitudes. We assumed two very contrasting, plausible Deimos compositions, a CI chondrite and a Shergotty Mars meteorite. We also included a small background due to neutrons from Mars, as well as a larger spacecraft background.

Table 5 shows the difference in background-subtracted thermal-plus-epithermal and epithermal counts ($\Delta C_{\text{therm} + \text{epi}}$ and ΔC_{epi}) between the two meteorite compositions, divided by their respective standard deviations, $\sigma_{\text{therm} + \text{epi}}$ and σ_{epi} . At a 10-km closest-approach altitude, a better than 2- σ difference in both thermal-plus-epithermal and epithermal counts would be measured with five flybys at 1 km/sec. At a 20-km closest-approach altitude, the epithermal difference is still >2- σ , but the thermal-plus-epithermal counts are different by only ~1- σ , and so unlikely to provide a definitive composition measurement. At closest-approach altitudes of 50 and 100 km, detection of Deimos above background statistics is questionable. Slower flyby speeds would improve the signal-to-background in the lower closest-approach altitude cases.

5. Status of MEGANE Development

As of this writing, the MEGANE investigation is in its preliminary design phase (Phase B). The current design work is focused on finalizing the various interfaces (mechanical, electrical, and operational) between the MEGANE hardware and the MMX spacecraft and mission. The current schedule calls for the detailed design phase to start in the spring of 2020, final delivery of the MEGANE instrument in the spring of 2023, and launch of the MMX spacecraft in the summer of 2024.

MEGANE will acquire the first elemental compositional measurements of Phobos, and will provide critical information to enable an understanding of Phobos' formation and the surface processes that operate on Phobos. In addition, data from MEGANE will play a key role in the MMX mission for carrying out orbital reconnaissance, helping to prepare for selection of the sample site(s), as well as providing compositional context for the detailed study of the returned Phobos samples.

Acknowledgments

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