DETECTING NEAR-SURFACE WATER AND HYDRATE MINERALS ON MARS FROM A ROVER, PENETRATOR, OR BOREHOLE: THE HYDRA INSTRUMENT. R. C. Elphic[1], D. J. Lawrence[1], W. C. Feldman[1], R. C. Wiens[1], R. L. Tokar[1], K. R. Moore[1], T. H. Prettyman[1], H. O. Funsten[1], [1]Los Alamos National Laboratory, MS D466, NIS-1, Los Alamos, NM, 87545, USA (relphic@lanl.gov)

1. Introduction: One of the major goals of near term NASA Mars exploration is to identify exact locations of near-surface water or hydrated minerals on Mars. Evidence for the existence of recent near-surface water on Mars [1] underscores the need for developing instrumentation that can identify water or hydrated minerals very near the surface. Further encouraging evidence of surface and near-surface water and hydrate minerals on Mars comes from neutron spectrometer measurements aboard Mars Odyssey. Preliminary results show very large regions of high hydrogen content poleward of 60° latitude, as well as interesting features closer to the equator [2]. However, spatial resolution from orbit is very poor, ~400 km. The next logical step is to use in-situ or near-surface investigations to map in detail some of the most interesting features. Relatively simple instrumentation based on ^{3}He gas proportional counters were shown to be highly successful on the Lunar Prospector mission in identifying even low levels of enhanced hydrogen abundances [3,4,5].

Here we discuss "HYDRA," a water- and hydrate-sensing instrument currently being developed under the NASA Mars Instrument Development Program (MIDP). HYDRA is based on Lunar Prospector technology, and is intended as a rover body-mounted instrument, or an instrument on an aerobot, penetrator, hard lander on the surface of Mars, or for borehole stratigraphy applications. Our proposed instrument would be ideal for such platforms as it would be small (<7 cm diameter by 10 cm long), low mass (<500 g), low power (< 1W), and have a low data volume per measurement. We use neutron spectrometry (a) because of its proven ability to uniquely detect and quantify hydrogen abundance, and (b) because the resources required by this approach (weight, power, size, telemetry bandwidth, and measurement time) are extremely low. This compact neutron spectrometer package, comprised of two small ^{3}He gas proportional counters, offers superior sensitivity, extensive flight heritage, and inherent ruggedness. These tubes have survived ~1500 g's of acceleration in penetrator tests.

In a landed application, HYDRA would help address many topics of interest to the Mars Exploration and Astrobiology communities: (a) nature and origin of stratified deposits; (b) water cycle(s) and temporal changes; (c) early water — oceans, aquifers, precipitation; (d) current extent/location/state of water; (e) polar cap processes and temporal changes; (f) where extremeophiles could survive on Mars; (g) paleoclimate — surface signatures and modeling; (h) stategies for future Mars exploration.

2. Science Background: Liquid water is considered to be fundamentally important for the genesis, nurture and sustenance of life. Evidence is mounting that Mars still has near-surface groundwater activity. Though very water-poor by terrestrial igneous standards, the SNC meteorites were found to contain evaporite minerals suggestive of groundwater activity within the past 1.3 Ga [6]. Further evidence has been found in the SNC meteorites indicating that Martian magmas carried significant amounts of water to the surface of Mars [7]. In the last few years there has been great interest in surface features indicative of near-surface water [8,9,10,11,12]. Much of this interest was generated by Mars Global Surveyor images of geologically young seepage and outflow channels attributed to liquid water. The sources of these channels were suggested to be only a few hundred meters or less below the surface [1].

Calculations have typically shown that the region equatorward of ~45 - 50° should be dry near the surface, and regions poleward of this latitude should (and apparently do) support near-surface ice in the present climate [13,14]. However, other studies have suggested water might also exist close to the surface near the equator. By considering the effect of recondensation of water vapor as it diffuses to the surface, models predicted the persistence of porous interstitial ice to relatively shallow depths even at the equator [15]. Models are strongly dependent on the thermal inertia of the surface material. For particulate material (soil), predicted depths of the steady-state ice table were as little as ~4 m at the equator on a broad scale. One could easily imagine variations with terrain, thermal inertia, etc. which might cause the depth to be even shallower in localized regions. On the other hand, predicted ice table depths in dense rock are 200 m or more near the equator.

Figure 1 shows a preliminary epithermal neutron count rate map made using data from the LANL-built neutron spectrometer aboard Mars Odyssey. The epithermal flux is inversely related to the concentration of hydrogen (in the form of hydrate minerals or water or both) in the soils and rocks. Dark blue areas are hydrogen rich, red and yellow areas are hydrogen poor. The epithermal flux observed from orbit varies by a large factor over the planet, denoting the huge range of

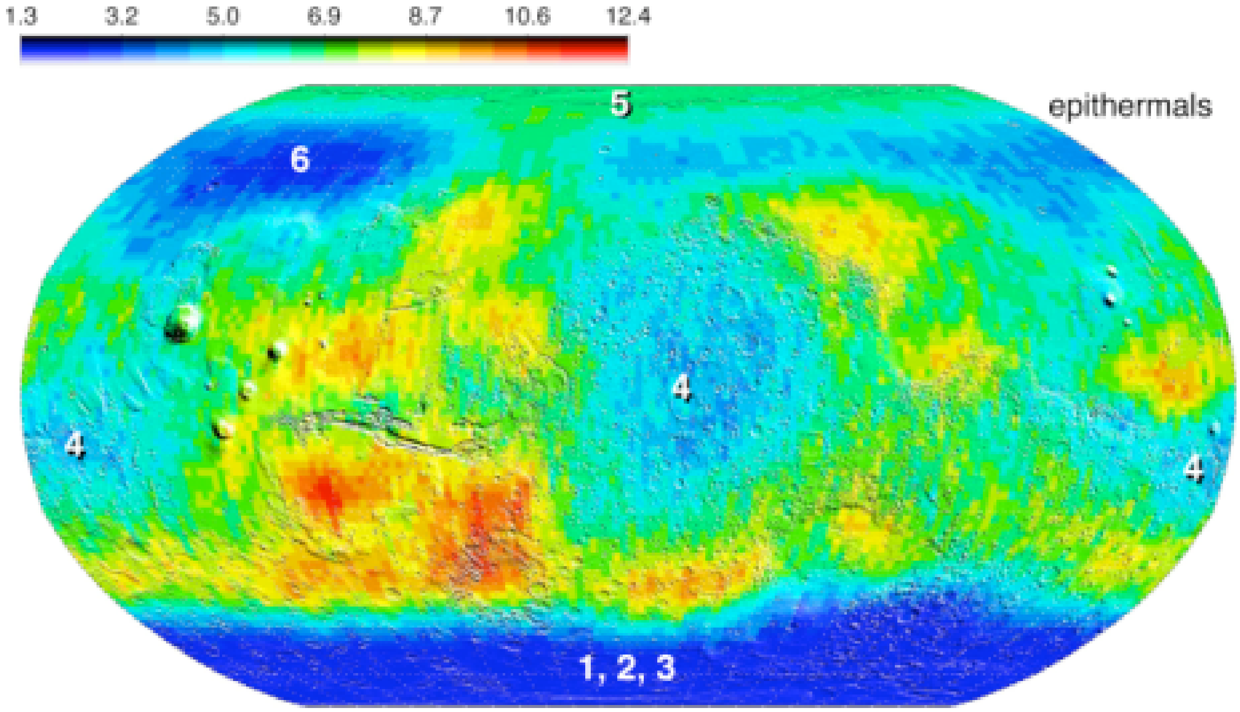

Fig. 1. Mars Odyssey epithermal count rate map for late northern winter at Mars. Low (blue) count rates correspond to regions rich in hydrogen (water), and high (red) count rates denote regions of reduced hydrogen content. Numbers are discussed in the text (see Feldman et al., this conference).

water/hydrate concentrations from location to location. According to [2], several regions can be identified in Figure 1. (1) the region south of -60° latitude is very rich in hydrogen, (2) it is buried beneath a relatively hydrogen-poor overburden, (3) the residual south polar cap is covered by a thick layer of CO_2, (4) large portions of near-equatorial highlands terrain may contain buried deposits of hydrogen-rich material, (5) the central portion of the north polar cap extending down to about +60° latitude is covered (in northern winter) by a thick layer of CO_2, (6) the equatorward margins of the north polar cap extending at places down to about +45° latitude contain buried deposits of hydrogen-rich material. Clearly hydrogenous materials at and near the surface of Mars are very prevalent, and hold clues to Mars' past history and present state.

The search for extant or fossil life on Mars will almost certainly concentrate on areas where abundant water is or was present. The identification of sedimentary rocks and in particular, hydrous minerals is of great importance for the astrobiology program. However, our experience so far shows that such an identification is not a simple task. The orbiting Thermal Emission Spectrometer (TES) found evidence for abundant, large-grained hematite in the Sinus Meridiani region [16], suggesting again that liquid water existed at some point on the surface of Mars. However, there is no evidence of hydrated minerals in the TES spectra. Unfortunately, *actual hydrated minerals are very unlikely to be found close enough to the surface to be revealed by imaging techniques*, given the desiccating effect of the Mars atmosphere and the reactive nature of the Martian soil [17]. Thus, the very minerals of greatest interest (as well as water) will most likely be found only at some depth below the surface. The best way to identify them directly is to drill for them. However, drilling is highly energy- and time-intensive. It is absolutely essential to know a priori where to drill.

An ultracompact neutron spectrometer is the perfect tool to determine the presence of buried hydrate minerals, or water at presently accessible depths, as its depth range is approximately 1 m.

3. Feasibility of Using Neutrons for Water and Hydrate Detection: Planetary neutron spectrometry is most easily carried out on airless or nearly airless bodies because of the large numbers of neutrons that are produced at the surface by energetic galactic cosmic rays (GCR). Specifically, when a planetary body has no or a very thin atmosphere, galactic cosmic rays constantly impinge on the surface and produce high-energy neutrons (~10 MeV) through nuclear charge-exchange, knock-on, and spallation reactions. The high-energy neutrons can lose energy either by elastically or inelastically scattering in the planetary material or they can be absorbed by neutron capture reactions. As demonstrated by various simulations and measurements [18,19,20], an equilibrium neutron flux develops which covers over nine orders of magnitude in energy from 0.01 eV to 10 MeV. The equilibrium neutron leakage flux out of the surface is naturally divided into three energy bands: thermal neutrons (E = 0.01 – 0.4 eV), epithermal neutrons (E = 0.4 eV – 0.5 MeV) and fast neutrons (E ~ 0.5 – 10 MeV). For thermal neutrons the dominant reaction is neutron capture and for epithermal neutrons the dominant reaction is energy loss (moderation) from elastic and inelastic scattering. In the presence of hydrogen (i.e., hydrated minerals or water), elastic scattering is an extremely efficient energy loss mechanism for epithermal neutrons. Enhanced hydrogen abundances lead to a large decrease (up to nearly two orders of magnitude) of the epithermal neutron flux from otherwise dry soil. Second-order epithermal flux variations can be caused by neutron capture reactions, but are tracked with the thermal neutron flux which is dominated by the neutron capture reactions.

The technique of using thermal and epithermal neutrons to detect hydrogen abundances on a planetary surface was first demonstrated with the Lunar Prospector Neutron Spectrometer (LP-NS) [3]. Orbital neutron spectrometers are also being used to measure hydrogen abundances on Mars (Mars Odyssey 2001), Mercury (MESSENGER), and the main belt asteroids Vesta and Ceres (DAWN). The LP-NS used two ^{3}He gas proportional counters to measure thermal and epithermal neutrons. A ^{3}He proportional counter works by unambiguously identifying the 765 keV reaction products that are emitted when a neutron is absorbed in the ^{3}He gas. One counter is wrapped in 0.63 mm of Cd and is sensitive only to epithermal neutrons (Cd absorbs all neutrons having energies less than about 0.4 eV). The other counter is wrapped in 0.63 mm of Sn and is sensitive to both thermal and epithermal neutrons [21]. The epithermal neutron flux is obtained by measuring the count rate in the Cd covered counter and the thermal neutron flux is obtained by measuring the count rate difference between the Sn and Cd covered detectors. While each ^{3}He tube of the LP-NS was relatively large (5.7 cm diameter by 20 cm length), the physics of thermal and epithermal neutrons permits their detection by very small packages. ^{3}He proportional counters are routinely made quite small (1.2 cm diameter by 4 cm long) while retaining very simple operational characteristics. For these reasons, ^{3}He counters make ideal instruments for use on a rover, penetrator, or other landed Mars application.

3.1 Feasibility of HYDRA on a Rover or Lander: We have carried out Monte Carlo simulations using MCNPX to determine the neutron signal levels that would be measured by HYDRA over soils of various water contents and at various depths. The MCNPX simulations were carried out for bare Cd and Sn tubes at the soil surface, and for tubes mounted on a rover [22]. The rover is simulated as a 150 kg mass 50x50x50cm in size, consisting of 90% Al and 10% PC board material (60% fiberglass, 40% epoxy). The soil composition was average Pathfinder soil [23]. The ^{3}He tube sizes for these simulations were 1 cm diameter by 16 cm long. Figure 2 shows the count rate (per minute) of the Cd-covered epithermal neutron detector as a function of both H_2O content and depth of burial of the water. Note first of all that the count rates are substantial, showing that cosmic rays are clearly a sufficient source for neutrons even with a very small detector. The top curve shows that even a 1% H_2O content buried beneath 70 cm of desiccated soil still shows a 10% reduction in the epithermal count rate. Higher water contents at shallower depths produce very marked reductions in count rate. Above ~20 wt% H_2O the sensitivity to actual water concentration saturates. Moreover, from epithermal fluxes alone it is not possible to distinguish between a higher concentration of water buried at a greater depth, or a lower concentration buried at a shallow depth. However, the thermal neutrons (not shown) also respond to the presence of buried water, and help remove the ambiguity. In any case, the HYDRA instrument serves as an effective prospecting tool for rapidly and simply locating hydrates or buried water to depths of many tens of

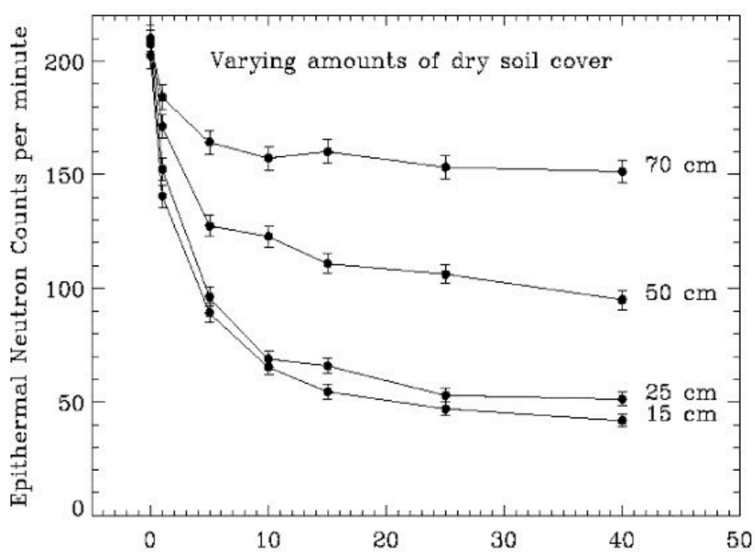

Figure 2. Epithermal neutron count rate for a Cd-covered ^{3}He tube carried by a rover over buried deposits of different water wt% and burial depths. [22]

centimeters even when the compact instrument is body-mounted on a rover platform.

Rovers or landers powered by an RTG actually enhance HYDRA's water-detection capabilities in the near-surface regions. An RTG provides a steady source of fast (~1 MeV) neutrons which penetrate the soil and are moderated by the hydrogen there [24]. Simulations confirm that HYDRA will perform very efficiently in such a configuration, which is promising for future exploration scenarios.

3.2 Feasibility of HYDRA for a Down-Hole Application: HYDRA can be a very sensitive and accurate means of obtaining a depth profile of water, water ice or hydrate minerals. Simulations have been run of the expected epithermal and thermal count rates as a function of depth for several different burial scenarios [25]. Figure 3 shows one set of results: three cases of a layer of 19wt% H_2O about 15 cm thick centered at roughly 17 cm depth, 23 cm depth, and 47 cm depth (all assuming a soil density of 2 g/cm^3), and an unlayered soil having 1wt% H_2O (short dashed lines). Both thermal and epithermal neutron count rates are shown assuming ^{3}He tube dimensions of 1 cm x 16 cm and a tube pressure of 10 atm. The thermal neutron count rate (upper left) goes up within the water-rich layer because thermal neutrons are wicked up from neighboring hydrogen-poor materials owing to the reduced scattering length in the hydrogen-rich layer. The epithermal count rates (upper right) drop within the layer because these neutrons are rapidly being downscattered out of the epithermal energy range. Finally, the ratio of thermal to epithermal count rates (lower left)

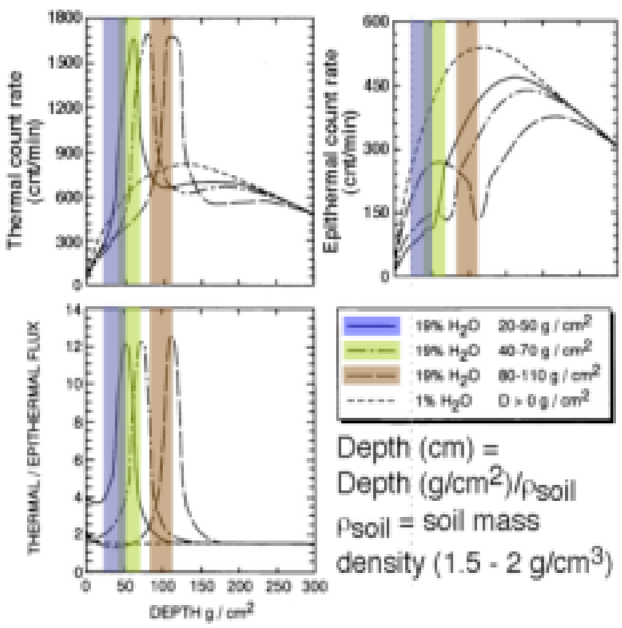

Figure 3. Thermal and epithermal neutron count rate as a function of depth for three H_2O-rich layers buried at different depths. Adapted from [24].

provides a very clear and unambiguous indicator of the depth, thickness, and water abundance in the layer. Consequently, a HYDRA sensor (configured to fit within a drill string segment) placed down a borehole can obtain a depth profile, a stratigraphic sequence of where wet and dry layers are found. This information is useful for sample extraction, providing both a stratigraphic context and promising locations for sample collection. Note that the neutron count rates shown in Figure 3 assume only cosmic rays as the source of neutrons; there is no need for the instrument to carry a neutron generator. In fact, cosmic rays will provide sufficient neutron count rates for useful measurements down to nearly 10 m. HYDRA also lends itself to use with an RTG-powered lander and drill [24].

HYDRA on a rover provides 2-dimensional near-sub-surface water and hydrate prospecting, while HYDRA in the borehole application provides the third dimension of depth.

References: [1] Malin M.C. and Edgett K.S. (2000) *Science 288*, 2330-2335. [2] Feldman, W. C. et al. (2002), *Science,*10.1126/science.1073541. [3] Feldman, W. C. et al. (1998), *Science, 281*, 1496 – 1500. [4] Feldman, W. C. et al. (2000), *J. Geophys. Res*., *105*, 4175 – 4195. [5] Feldman, et al.(2001), *J. Geophys. Res., 106*, 23231-23251. [6] Bridges J.C. and Grady M.M. (2000) *Earth Planet. Sci. Lett. 176,* 267-279. [7] McSween H.Y., et al. (2001) *Nature 409*, 487-490. [8] Haberle R.M., et al. (2001) *J. Geophys. Res. Planets*, 106, 23317-23326. [9] Masson P., et al. (2001) *Space Science Reviews 96*, 333-364. [10] Mustard J.F., et al. (2001) *Nature 412*, 411-414. [11] Mellon M.T. and Phillips R.J. (2001) *J. Geophys. Res. Planets 106*, 23165-23179. [12] Baker V.R. (2001) *Nature 412*, 228-236. [13] Mellon M.T. and Jakosky B.M. (1993) *J. Geophys. Res. 98*, 3345-3364. [14] Titus, T. N., et al. (2002), *Science,* 10.1126/ SCIENCE.1080497. [15] Mellon M.T., et al. (1997) *J. Geophys. Res. 102*, 19357 – 19369. [16] Christensen, P. R. et al. (2000) *J. Geophys. Res. 105*, 9623-9642. [17] Zent A.P. and McKay C.P. (1994) *Icarus 108*, 146-157. [18] Lingenfelter, R. E. et al. (1961) *J. Geophys. Res.*, 66, #9, 2665 – 2671. [19] Drake, D. M. et al. (1988) *J. Geophys. Res*., 93, #B6, 6353 – 6368. [20] Maurice, S. et al. (2000) *J. Geophys. Res*., *105*, 20365-20375. [21] Feldman W.C. et al. (2001) *J. Geophys. Res., 106*, 23231-23251. [22] Lawrence, D. J., et al. (2002), *Lunar Planet. Sci. XXXIII*, abstract #1597 (CDROM). [23] Bruckner et al. (2001) *Lunar and Planet. Sci. XXXII.,* Abstract #1293 (CDROM). [24] Lawrence, D. J. et al., this conference. [25] Feldman, W.C. et al. (1993) *J. Geophys. Res. 98*, 20855-20870.