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## Concepts and approaches to in situ luminescence dating of martian sediments<sup>☆</sup>

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### Abstract

In this paper we present the concept of a robotic instrument for in situ luminescence dating of near-surface sediments on Mars. The scientific objectives and advantages to be gained from the development of such an instrument are described, and the challenges presented by the Mars surface environment to the design and operation of the instrument are outlined.

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### 1. Introduction

Recent missions to Mars have revealed that the planet's surface has been subjected to geologic and climatic processes throughout its history—including aeolian, fluvial, periglacial, and volcanic activity (Malin and Edgett 2000; Kieffer et al., 1992). However, so far the only available chronologies for Mars are based upon relative crater densities and the assumption that the planet has been exposed to a crater flux similar to that of the Moon. These assumptions

have led to age uncertainties for younger terrain (< 1 Ma) that are of the order of the ages themselves. In order to constrain younger ages either returned samples are required or in situ methods for obtaining absolute dates of surfaces and geomorphologic features need to be developed.

Establishing a chronology for these events is essential to interpret the planet's geomorphologic and climatic history (Doran et al., 2000). Although Mars is too cold with too thin an atmosphere to sustain liquid water on its present surface many of the observed features, often associated with crater or canyon walls, appear to show evidence of "recent" deposition events caused by surface water flow, and suggest the emergence of sub-surface water with associated erosion (Malin and Edgett, 2000). Example images are shown in Fig. 1. In contrast, however, suggestions have been made that some of these features may, in fact, be wind-blown—i.e. aeolian (Howard, 2000). Certainly extensive aeolian

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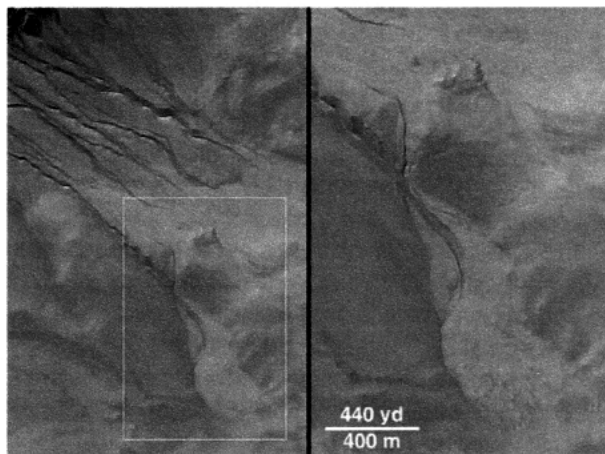


Fig. 1. MGS MOC Release No. MOC2-241, 22 June 2000 image (Malin et al., 2000) (<http://www.msoss.com>). Channels and debris apron from the NW corner of a 17-km diameter impact crater (37.4°S, 168.0°W) in the Gorgonum Chaos region. There are no impact craters in the apron, suggesting a very young age (“modern?”).

features can be identified all over the martian surface, and occasional dust storms are observed to be active even today. Aeolian dune fields are observed extensively, and layered terrain near the poles indicates periodic aeolian activity.

Considerable accumulations of aeolian material can be found at the poles, where km-thick mantles of frozen sediment and ice form polar caps that are among the youngest terrains to be found on Mars (Clifford et al., 2000). The estimated age of the exposed surface in the north is less than about  $10^5$  years while in the south, the identification of  $\sim 15$  craters with diameters  $> 800$  m (Plaut et al., 1988) indicates a surface age of 7–15 million years, depending on the recent Martian cratering flux (Herkenhoff and Plaut, 2000).

The two geologic units common to both poles are: (i) the residual polar ice cap and (ii) the polar layered deposits (Murray et al., 1972; Soderblom et al., 1973; Tanaka and Scott, 1987). The two units are distinguished by their temperatures and albedos, but the residual caps may simply be the most recent layer in the process of forming. The polar layered deposits are characterized by numerous, laterally extensive, horizontal layers that have apparent individual thicknesses ranging from  $\sim 300$  m down to the resolution limits of the available imagery ( $\sim 1.5$  m/pixel) (Blasius et al., 1982; Herkenhoff and Murray, 1990; Thomas et al., 1992)

While many details are uncertain, a general consensus has developed regarding the constructional processes responsible for the origin of the polar layered deposits. An essential element of this model is the idea that atmospheric dust, raised by local and global dust storms, acts as nucleation centers for H<sub>2</sub>O ice condensation. As either hemisphere enters the fall season, these suspended particles receive an

additional coating of frozen CO<sub>2</sub> that makes them heavy enough to precipitate from the atmosphere, thus contributing to the growth of both the seasonal and permanent caps (Cutts, 1973; Pollack et al., 1979). A significant contributor to the growth of the polar caps has been the deposition and entrainment of dust, scavenged from across the planet by frequent local and global dust storms (Murray et al., 1972; Soderblom et al., 1973; Cutts, 1973). In the same way, ash from volcanic eruptions, fallout from large impacts, evaporites from sublimating lakes and seas, and perhaps even samples of microbial life, may have been brought to the poles and precipitated from the atmosphere, to be embedded and preserved within the growing mantles of frozen sediment.

Thus, the extensive layering observed within these deposits, suggests that they may preserve a stratigraphic record that ranges from months to millions of years, modulated by quasi-periodic changes in the planet’s orbit and obliquity (Murray et al., 1972; Cutts, 1973; Toon et al., 1980; Howard et al., 1982; Cutts and Lewis, 1982; Herkenhoff and Plaut, 2000). By analogy with the major ice sheets of Earth, these deposits may serve as a “Rosetta Stone” for understanding the recent geologic and climatic history of Mars (Clifford et al., 2000) by documenting variations in: (a) volatile mass balance, (b) insolation (due to quasi-periodic oscillations in the planet’s obliquity and orbital elements), (c) atmospheric composition, (d) dust storm activity, (e) volcanic eruptions, (f) large impacts, (g) catastrophic floods, (h) and perhaps even a record of microbial life. A critical requirement for interpreting this complex record is the need for absolute dating, preferably by techniques that can be applied in situ to establish an accurate chronology of the polar stratigraphy. Such capabilities would dramatically enhance the potential scientific advantages of a possible mission to the poles in the latter half of this decade.

While several chronometric dating techniques are utilized in terrestrial studies, not all are easily adaptable to remotely operated probes on the Martian surface, nor do they date the same event. Of primary interest in the interpretation of any of the geomorphologic features referred to above are the ages of the various aeolian (and possibly fluvial) depositional events, be they in the polar layered terrain or elsewhere on the planet, and their relevance to climate variation and evolution. Three dosimetric techniques that have the potential to date these events, and perhaps to identify the origin of near-surface sedimentary deposits (fluvial or aeolian), are thermoluminescence (TL), optically stimulated luminescence (OSL), and electron spin resonance (ESR). This paper is concerned with the potential development of an in situ instrument for dating near-surface depositional events using OSL. The science objectives of in situ luminescence dating systems on the Martian surface would include: (a) determining the frequency of aeolian dust storms; (b) characterizing the development of the polar layered stratigraphy; and (c) establishing a time scale for apparent fluvial activity. In this paper we ask the question “how feasible is it to design a robotic in situ instrument for OSL

dating?" and briefly mention the potential for in situ TL and ESR instrumentation also. We consider the unique challenges presented by the Martian surface environment and discuss the various concepts and the possible approaches that may be used in the design of a low-power, low-weight, in situ luminescence dating instrument.

## 2. The challenges

### 2.1. The martian surface; mineralogy

Luminescence dating on Earth has concentrated upon the most ubiquitous of natural minerals—namely quartz and feldspar. Constraints upon the minerals to be expected on Mars have been established by in situ analysis (the Pathfinder and Viking missions) and remote sensing (Mars Global surveyor and Odyssey). These data indicate ferric oxides in the regolith and dust, weathered basalts and andesite, including plagioclase and clinopyroxene, along with finer particles of iron-rich clays, sulfates, and carbonates (Bell et al., 2000; Morris et al., 2000). Thus, an in situ instrument would be required to work with a wide variety of mineral components. Since wet-chemical mineral separation and detailed sample preparations of the type familiar to luminescence dating practitioners on Earth are not feasible for a robotic in situ instrument, development of techniques to date polymineral samples, containing minerals other than quartz or feldspar, is required. Although progress has been made on dating polymineralic terrestrial minerals using OSL (e.g. Banerjee et al., 2001) it is clear that OSL characterization work is necessary on a wide range of terrestrial minerals which may be viewed as martian analog materials, such as sulfates, carbonates, iron oxides, clay minerals, sandstones, and granites. In addition, studies are required on the SNC meteorites and other martian soil simulants (such as the JSC Mars-1 soil simulant; Allen et al., 1998) in order to provide perhaps the closest analogs to actual martian soils.

These characterization studies will follow the previous work by Lepper and McKeever (2000) and Banerjee et al. (2002) on JSC Mars-1 soil simulant. It will be necessary to establish that an increasing OSL signal with absorbed dose can be reliably obtained, and that the OSL signal is responsive to martian ambient sunlight (i.e. the signal bleaches efficiently when exposed to sunlight). Although Mars is further from the Sun than Earth, the reduced solar flux at the top of the atmosphere (only 43% that of Earth) is compensated by a thin CO<sub>2</sub> atmosphere resulting in an increased flux at the surface, particularly in the UV range (Kuhn and Atreya, 1979). Thus, bleaching is expected to be efficient, subject to the existence of suitable optically sensitive charge traps within the available minerals. An additional requirement of a mineral suitable for dating is that the signal be stable over the lifetime of the feature being dated. This includes both thermal stability (i.e. the existence of sufficiently energetic

traps) and no non-thermal, or anomalous, fading. TL and OSL studies of the Mars soil simulant JSC Mars-1 (Lepper and McKeever, 2000; Banerjee et al., 2002) have indicated that it possesses the required properties of an increasing luminescence signal with dose (with saturation doses of the order of several kGy), and OSL signals that bleach effectively in sunlight (on Earth). However, as expected from this simulant material (which is a volcanic ash sample from Hawaii; Allen et al., 1998), clear indications of heterogeneous anomalous fading were observed (Lepper and McKeever, 2000; Banerjee et al., 2002).

### 2.2. Anomalous fading

The necessity to conduct OSL measurements on quartz poor polymineralic samples, many of which may contain minerals of probable volcanic origin, leads to the issue of potential anomalous fading of the luminescence signal over geologic time periods. This luminescence instability has been documented in feldspar (of any origin) and it has so far constrained the application of this material in luminescence dating on Earth. However, recent developments, applicable in the Mars context, have emerged which raise hopes for correcting for anomalous fading effects. There are those methods that correct for fading, such as the *fadia* method (Lamothe and Auclair, 1999). With this method one seeks to determine the extent of anomalous fading of the luminescence and to evaluate the *apparent* age among heterogeneous sub-samples. The true age is then found by extrapolating to zero fading. This method is most suitable for samples exhibiting a large range of fading behavior, hence its name. In another approach suggested by Huntley and Lamothe (2001), one assumes that the measured fading rate in the laboratory can be extrapolated over geologic times. Using a simple mathematical model to describe the fading process the 'correct' age is found following an iterative procedure. It is interesting to note that for young samples, both methods can be applied since they are each based on the measurement of the fading rate (the so called '*g*' value of Aitken, 1985). Other approaches to the problem attempt to identify a stable luminescence signal—i.e. one that does not fade. Following the early work of Zink and Visocekas (2000) and more recently Stokes and Fattahi (2002), the red luminescence emission from feldspar is suggested to be stable over geological time. Here, however, the detection of red luminescence may place constraints upon the choice of light detection components, many of which are insensitive in the long-wavelength region of the visible spectrum. This may be an important consideration since the experimental design requires the use of small sample sizes with a commensurate low luminescence emission intensity. Finally, inasmuch as there might be sufficient quartz or other, non-feldspathic material in the investigated samples, the measurement of the OSL using green or blue stimulation following the removal of the unstable luminescence component by a pre-exposure to IR stimulation (so called "post-IR blue" (or green)

stimulation; Banerjee et al., 2001), may be a pathway worthy of further study for this application.

### 2.3. The martian ambient temperature

Previous work on TL and OSL from JSC Mars-1 (Lepper and McKeever, 2000; Banerjee et al., 2002) as well as nearly all characterization studies on terrestrial minerals for dating purposes (Wintle, 1997), have been conducted with irradiation and optical stimulation at or above room temperature. However, the average surface temperature on Mars is only 210 K (Kieffer et al., 1992) and the diurnal temperature variation can reach as low as 170 K to as high as 300 K, depending on location. A lower ambient temperature for irradiation, storage, and stimulation may have significant effects on the dynamics of the luminescence process. Charge traps that are not accessible under terrestrial ambient conditions may be filled by irradiation at low temperatures; traps that are normally not considered stable could have increased stability. Furthermore, since many OSL processes are often thermally assisted in some way the effectiveness of optical stimulation may be very different at lower temperatures. To investigate these phenomena, measurement of the OSL properties of martian regolith simulants at low (martian ambient) temperatures is required in order to test the efficiency of stimulation at low temperature, to determine the OSL dose-response characteristics, to identify suitable pre-heat procedures, and to conduct dose recovery experiments.

### 2.4. The radiation environment

The surface radiation environment consists of a continuous flux of high energy protons, electrons and heavier charged particles from galactic cosmic rays (GCR), and solar particle events (SPE). The resultant absorbed dose due to GCR and SPE particles at the surface of Mars is significantly higher than at the surface of Earth. Environmental doses due to trace quantities of U, Th and K, however, are believed to be less than those on Earth, using data from martian meteorites (Shubert et al., 1992). As a result, perhaps the most important component of the environmental dose rate is from the GCR and SPE sources.

The radiation environment on the surface of planet Mars is estimated using four factors: the ambient radiation environment, the properties of the martian atmosphere, the properties of the martian surface, and the radiation interaction models. Models to describe the radiation environment include all four components. In these models solar modulated galactic cosmic ray calculations are rescaled for Mars conditions. The calculations follow the transportation of the GCR through the martian atmosphere, with temporal properties modeled with variable timescales, down to the surface, with altitude and backscattering patterns duly taken into account. The martian atmosphere has been modeled using the Mars Global Reference Atmospheric Model (Mars-GRAM 2001). The altitude data needed to compute the atmospheric

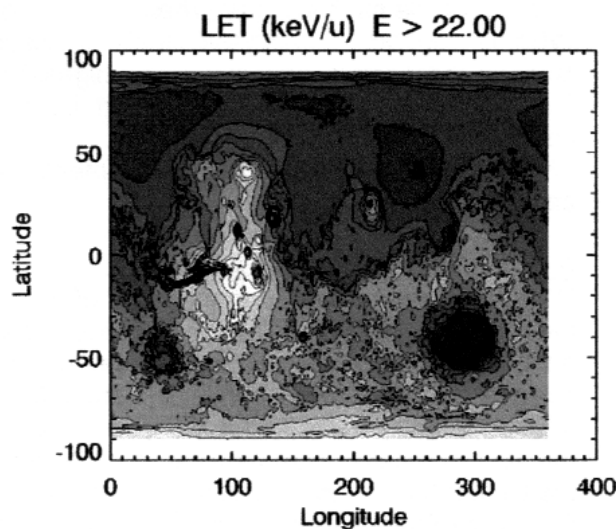


Fig. 2. Contour maps of the integral fluence of particles on the martian surface with LET > 22 keV/μm. Red represents high intensity and blue represents low intensity.

thickness profile have been obtained by using a model for the topography based on the data provided by the Mars Orbiter Laser Altimeter (MOLA) instrument on board the Mars Global Surveyor (MGS) spacecraft. The surface properties of Mars have been modeled based on measurements obtained at the various Viking and Pathfinder landing sites, taking into account variations in volatiles throughout the martian year. The present model simplifies the volatiles by ignoring the longitude dependence, which mainly affects the surface neutron environment. Particle transport has been performed with the neutron-multigroup version of the HZETRN code (High Z (atomic number) and energy transport; Wilson et al., 1995). As an example calculation Fig. 2 shows a contour map of the integral fluence of particles on the surface with LET > 22 keV/μm at 1235 UT November 12, 2056. Using these data the average annual surface dose is calculated to be 51 mGy from GCR particles and 2.7 mGy from SPE particles (based on an 11-year solar cycle). Calculations of the attenuation of the dose with depth beneath the regolith surface are indicated in Fig. 3. Estimates from martian meteorites suggest an average background dose rate of just 0.4 mGy/year due to U, Th and K (Milekowsky et al., 2000). Thus, the radiation environment is dominated by external radiation, even down to depths of > 2 m. Although the dose is due to all particles, 95% of the absorbed dose is from particles with linear energy transfer (LET) less than ~ 10 keV/μm (Benton and Benton, 2001) and these are the particles which will produce the OSL signals in the regolith materials.

Determination of the annual dose rate is thus simplified for those deposits that are shallow (less than, say, 2 m) and are stratigraphically stable. For such deposits we can estimate a fixed annual average of approximately 54 mGy/year.

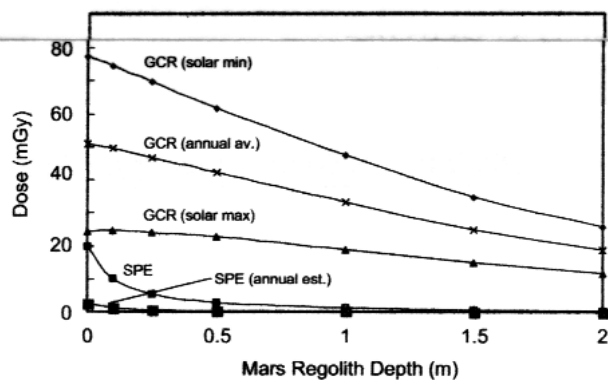


Fig. 3. Radiation transport calculations of dose-versus-depth for GCR and SPE particles. Calculations for the GCR flux at both solar minimum and solar maximum and an estimated annual average are indicated. Also indicated are SPE calculations using data from a recent solar flare (March 1991) and the estimated annual SPE average dose.

These estimates are a global average and can be refined for the particular location of any future landing. On the other hand, estimates of ages for deeply buried deposits would require a measurement or estimate of the background dose rate due to the presence of natural radioisotopes. Such estimates, if required, would be more problematic. A third scenario involves those deposits which are unstable and are continuously being buried due to the deposition on additional regolith layers on top. In these cases, the annual dose rate cannot be considered constant and more sophistication needs to be introduced into the models for dose rate determinations, including an estimated average burial rate. It is important to note, however, that the difference in the dose rate at the surface and at a depth of (say) 2 m is only a factor of  $\sim 2$  (Fig. 3). Thus, use of a fixed dose rate when calculating the age—appropriate to the current (excavated) burial depth—will still yield an estimated age for the deposit which is within a few hundred percent of the real age. Although such uncertainties would be unacceptable for terrestrial deposits they would represent a significant advance in our current knowledge of the martian geomorphological history.

### 2.5. Age range

Measurements on terrestrial silicate minerals indicate a saturation level for the OSL signal of the order of  $10^3$ – $10^4$  Gy. Using this, one estimates that potential maximum ages of  $10^3$ – $10^6$  years can be determined with OSL, depending upon depositional environment (i.e. primarily depending upon depth). Thus, samples from deep drilling can potentially be dated over the past  $10^6$  years (if one assumes a constant burial depth) while dating of near-surface deposits will be limited to more recent periods.

## 3. Instrument considerations

Low power, low volume, low weight and economical data acquisition are common requirements for all components of instrument systems on spacecraft. The anticipated flight mass of the unit would be 2–3 kg, housed in a package of approximate volume  $15 \times 20 \times 20$  cm<sup>3</sup>. The electrical power consumption is estimated to be several watts. Additional considerations include the following:

### 3.1. OSL stimulation sources

Considering that the mineralogy upon which the method will be focussed is only broadly defined, a combination of visible (green) and infra-red stimulation sources will probably be required. Ultra-bright LED arrays or diode lasers may be sufficient. We have monitored the stability of Nichia InGaN green LEDs as a function of radiation and at low temperatures. The LEDs are radiation hard in that their performance does not degrade (peak emission stable within  $\pm 1$  nm, and output intensity stable within  $\pm 5\%$ ) as a function of gamma dose up to absorbed doses of 500 Gy. Additionally, the emission spectrum remained constant and the power output increased when operated in constant current mode (2 mA) at low temperatures, down to  $-160^\circ\text{C}$ . Thus, these devices will provide suitable stimulation sources for OSL dating of martian sediments.

### 3.2. Light detection system

Similarly, a sensitive, broad-spectrum detector is required. An essential feature will be the ability to detect in the near UV and short-wavelength visible regions, with additional detection capabilities in the red also desirable. Avalanche photodiodes (APD) are possible, although the performance of APDs and PIN diodes at low temperatures needs to be characterized. Miniature, ruggedized photomultiplier tubes should also be considered.

### 3.3. Irradiation system

Since the low LET part of the GCR and SPE spectrum dominates the absorbed dose, one can calibrate the samples with a single, low-LET source. Radioisotopes have the advantage of size, but require significant (i.e. heavy) shielding on the almost-one-year journey to Mars, particularly if one wishes to provide calibration doses of several hundreds of Gy within a short period. Thus, low activity sources have the disadvantage of long irradiation times during calibration. A low power, high-dose-rate, miniature X-ray tube is thus preferred. Commercial sources exist operating at 40–50 kVp, with an equivalent activity of approximately 1 Ci. Such sources have the advantage of being switched off when not in use and do not require shielding. Recent studies have demonstrated the utility of such X-ray sources in

luminescence dating (Hashimoto et al., 2002; Anderson et al., 2003).

### 3.4. Sample collection and handling

For a rover- or lander-based instrument, sample collection will likely be via a robotic arm. A few grams of material can be deposited into a sample hopper which will perform grain size and magnetic separation on regolith grains. Polymineralic aliquots of grain sizes up to 200–300  $\mu\text{m}$  and with masses of approximately 5 mg will be likely. Multiple aliquots (20–30) will be analyzed at each site. For an OSL and/or TL system a turntable will transport the samples from the sample hopper to the OSL readout and analysis chamber, and to the irradiation chamber. Metallic sample holders could be used. Alternatively, for an ESR system, ceramic, non-magnetic sample holders would be required, and a linear (belt or chain) transport system would be necessary to transport the sample through the sample cavity.

It is expected that the sediment grains in the aeolian dunes are sand-sized (Greeley et al., 1992) while the grain sizes of the sediments trapped within the ice layers are more poorly constrained but may range from fine silts to sand-sized particles (Clifford et al., 2000). A potential difficulty, the effect of which is difficult to assess at this stage, is that clumping of fine grains into sand-sized grain clusters may occur (Smalley and Krinsley, 1979). The clumping can be due to cementation by various salts, or due to electrostatic

charging during grain transportation (Gross et al., 2001). Electrostatic charging may also be induced during sample handling following excavation and collection.

### 4. A conceptual instrument

One potential conceptual OSL instrument design, which incorporates the above design elements, is illustrated in Fig. 4. The addition of ESR as a measurement tool is possible due to the development of a miniature, frequency-scan ESR spectrometer based on a dielectric resonator and a Halbach dipole magnet (Kim et al., 1997). The capability to perform TL may also be plausible using either a joule heater (with the corresponding additional electrical power burden) or a laser heating system using an IR diode laser.

### 5. Conclusions

The concept of an in situ, robotic OSL dating instrument for planetary exploration presents exciting prospects for unraveling certain aspects of the complex chronology of the martian surface. Far from being a “dead” planet, the surface of Mars exhibits geomorphologic features which suggest “recent” complex aeolian, fluvial, periglacial and volcanic activity. The issue in critical need of addressing, however, is to determine how “recent” is “recent”. The success of OSL dating on Earth leads to its consideration as a chronological

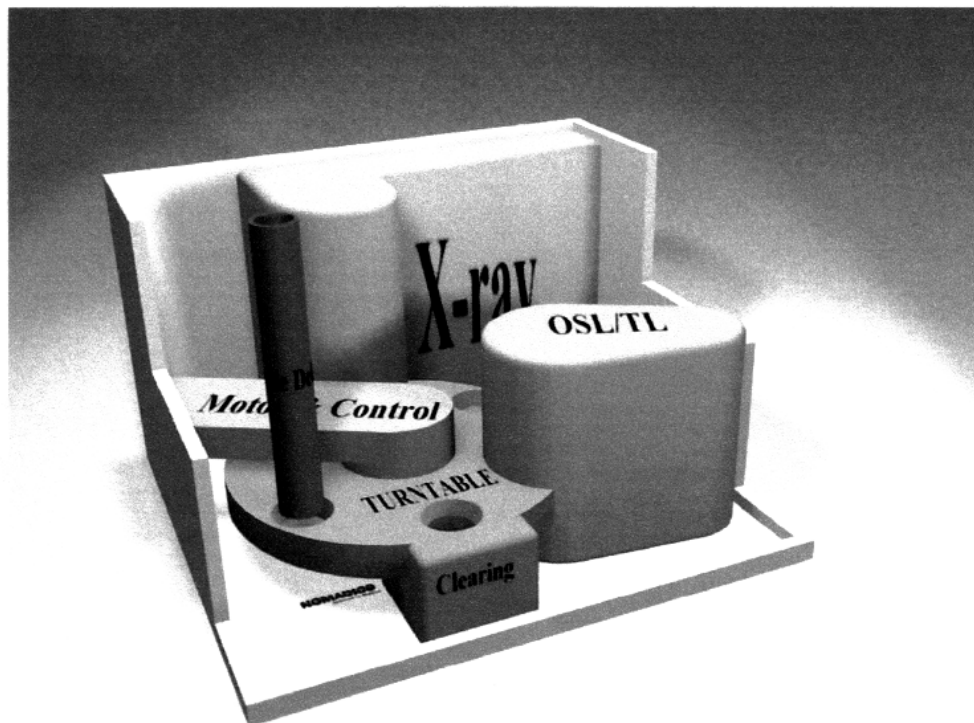


Fig. 4. An artist's impression of a conceptual instrument design for in situ luminescence dating of martian sediments.

tool on Mars. The martian arena, however, is one which is substantially different from the OSL dating scenarios we are used to dealing with on Earth. Complex and unknown mineralogy, poorly defined sample grain size distributions, high cosmic ray dose rates, less-well-understood geologic contexts, and low temperatures are among the challenges that need to be addressed. These challenges will require concerted efforts across multiple disciplines. Nevertheless, despite the challenges, the effort is worthwhile because, if successful, the scientific reward will be immense.

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