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MINERALOGICAL REVELATIONS FROM SPACE ODYSSEYS

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Nancy Ross

Sir Arthur C. Clarke (1917–2008), perhaps best known for the 1968 book and film *2001: A Space Odyssey*, once stated that "The only way of discovering the limits of the possible is to venture a little way past them into the impossible." As you enjoy this issue of *Elements* on planet Mercury, think about the remarkable achievement of sending a spacecraft to Mercury, the closest planet to the Sun.

Getting to Mercury is difficult, not only because the speed required to reach it is relatively high but also because the Sun's gravitational field pulls on any spacecraft that is sent into Mercury's orbit. The NASA *MESSENGER* probe, launched 2004, was the first to orbit Mercury and, as described in this issue, revealed many unique and enigmatic aspects of the planet. On 20 October 2018, the ESA/JAXA *BepiColombo* spacecraft was launched and began its seven-year journey to Mercury. This mission joins a myriad of other spacecraft sent out to explore the solar system's planetary expanse. On 5 November 2018, *Voyager II*, which was launched in 1977 on a mission to explore the outer planets, exited the heliosphere and entered interstellar space after flybys of Jupiter (1979), Saturn (1981), Uranus (1986) and Neptune (1989). On 26 November 2018, the NASA *InSight* lander safely touched down on Mars. It is the first space robotic explorer designed to study the interior of a planet by using seismology, geodesy, and heat flow measurements. On 3 December 2018, the NASA spacecraft *OSIRIS-REx* reached the carbonaceous asteroid Bennu and discovered the presence of water. On 3 January 2019, China successfully landed the *Chang'e-4* spacecraft on the far side of the Moon, this probe carrying a suite of instruments to analyze this unexplored region.

Each of these, and other, missions gather data from "natural laboratories" that encompass a wide range of composition, pressure, and temperature conditions. The acquired data answer some questions, but typically raise more, about the origin and evolution of our planetary system. For example, one of the surprising findings of the *MESSENGER* mission to Mercury was the unusually high sulfur and low FeO content of its surface lavas, suggesting highly reducing conditions during its formation. As described by Cartier and Wood (2019 this issue), insights into these redox conditions can be gained from studying the possible building blocks of Mercury, such as enstatite chondrites which are also highly reduced. These chondrites contain a wide variety of unusual sulfides, including the alkali copper–iron sulfide mineral, djerfisherite, with composition $K_6(Fe^{2+},Cu,Ni)_{25}S_{26}Cl$. I must admit that I was not familiar with djerfisherite and intrigued by its complex chemistry. It turns out that djerfisherite has an elegant structure with sulfur atoms arranged in a cubic close-packed arrangement and edge-sharing FeS_4 tetrahedra forming Fe_8S_{14} clusters that form the backbone of the structure. The iron atoms themselves form perfect cubes and, with interatomic separations of 2.74 Å, there are likely Fe–Fe bonded interactions that may account for the material's semiconductor properties.

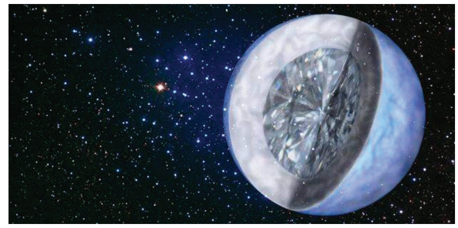

FIGURE 1 Artist's rendition of the "super-Earth" planet 55 Cancri e, in the constellation of Cancer, which was initially dubbed the "diamond planet". Note the core! IMAGE CREDIT: TRAVIS METCALFE AND RUTH BAZINET, HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

Some of the most fascinating mineralogical revelations are coming from the discovery of exoplanets orbiting stars beyond our solar system. On 30 August 2004, an exoplanet now named 55 Cancri e was discovered 40 light-years away in the constellation of Cancer the crab (McArthur et al. 2004). The mass of this exoplanet is about 8.63 times that of Earth, and its diameter is about twice that of the Earth. This classes it as a "super-Earth" planet. Similar to Mercury, 55 Cancri e is the innermost known planet in its planetary system, but its orbital year takes less than 18 hours (!) compared to the 88 days for Mercury. In 2012, it was announced that 55 Cancri e could be a carbon planet (Madhusudhan et al. 2012), and speculations arose that it could have a diamond-rich interior (FIG. 1). Interestingly, in Arthur C. Clarke's 1982 book sequel, *2010: Odyssey Two*, one of his extraterrestrial characters discovered that "the core of Jupiter, forever beyond human reach, was a diamond as big as the Earth." While the diamond hypothesis has been challenged (Teske et al. 2013), studies are ongoing to explain the unusual properties of 55 Cancri e. Indeed, the discoveries of 55 Cancri e and other super-Earth planets have motivated a number of theoretical and experimental studies that are expanding our knowledge of the stabilities of materials under extreme conditions of pressure and temperature.

It is time to end my odyssey into space and return to Earth. As I have time to reflect, it is clear that mineralogists have a rich and diverse playground of natural laboratories in which to explore the state of matter. The field of mineralogy is well positioned to expand along with the space missions and to embrace the amazing discoveries about the materials that comprise the universe.

Nancy L. Ross, Principal Editor

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