6

Mercury's surface-bounded exosphere

6.1 LIGHT EMITTING GASES

In the space surrounding Mercury atoms rarely collide, and, therefore, it is properly termed an exosphere rather than an atmosphere where the atoms are in constant collision. For decades carbon dioxide (CO_2) was thought to be the most likely gas in Mercury's exosphere because it had been discovered on Mars and Venus. Several attempts with ground-based spectrographs were made to find CO_2 absorption bands during the 1960s and 1970s but no absorptions were found. This was not too surprising because Mercury is a small planet with relatively low gravity and it was not likely that any gases ejected into the exosphere early in its history would remain bound to the planet. Nevertheless, *Mariner 10* was equipped with instrumentation to search for potential atoms and molecules in the exosphere, and made the first discoveries during the three flybys of Mercury in 1974 and 1975 as described in Chapter 2.

6.1.1 Hydrogen, helium, and oxygen

In *Mariner 10* airglow experiments, limited wavelength bands were predetermined based upon optical requirements and expectations of what might exist in an entirely unknown exosphere. Hydrogen (H), helium (He), and oxygen (O) were identified with the airglow polychromater that had 10 wavelength channels to search for light emissions. Upper limits on the abundance of neon (Ne), argon (Ar), and carbon (C) were also obtained.

6.1.2 A serindipitous discovery

The amount of light coming from the Sun's photosphere varies with wavelength because atoms in the photosphere absorb sunlight coming from deeper in the Sun.

Table 6.1. Mercury's exospheric species.

Constituent	Vertical (zenith) column abundance (atoms per cm^2)
Hydrogen (H)	$\sim 5 \times 10^{10}$
Helium (He)	$\sim 2 \times 10^{13}$
Oxygen (O)	$\sim 7 \times 10^{12}$
Sodium (Na)	$\sim 2 \times 10^{12}$
Potassium (K)	$\sim 1 \times 10^{10}$
Calcium (Ca)	$\sim 1 \times 10^{7}$

Such absorption lines are called *Fraunhofer lines*. When sunlight is reflected off the surface of the Moon, or Mercury, or any other Solar System body, the Fraunhofer lines appear as distinct regions of less sunlight than the average. The average is called the *continuum*. In 1985, planetary astronomers Andrew Potter and Thomas Morgan were studying a phenomenon called the Ring Effect (the infilling of solar Fraunhofer lines in the reflected continuum from the lunar surface). For comparison, they shifted their view to Mercury and observed significant emission lines high above the continuum at 5890 and 5896 Å. They had discovered Sodium (Na), the first new species in Mercury's exosphere since *Mariner 10* in 1974. This discovery renewed ground-based search efforts to find more atmospheric components. Discovery of potassium (K), calcium (Ca) and an upper limit on lithium (Li) have followed.

Table 6.1 shows all known constituents of Mercury's exosphere and their approximate abundances. The abundances of Na and K are known to vary by a factor of 10 or more from one measurement to the next or even at different locations above the planet during the same observation period. Probably the abundance of other species also varies but we do not have enough observations to be certain. Zenith column abundance refers to the column of atoms extending in a vertical direction from the ground to the top of the exosphere with the column foot print being a square with 1 cm length sides or 1 square centimeter. Because measurements do not measure the vertical column directly, the zenith column abundance depends upon the model used to calculate its value. The model is based on actual measurements. The Earth's atmosphere has $\sim 2 \times 10^{18}$ molecules per square centimeter.

6.1.3 Sunlight interacting with matter

All of the known species have been discovered by measuring the emission of solar *photons* from the atoms of Mercury's exosphere after interaction with the electrons in these atoms. Each type of atom has one or more wavelengths at which it absorbs and reemits sunlight. The particular wavelength is determined by the electronic structure of the atom. Light absorbed and emitted at the same wavelength for a particular species, it is called *resonance scattering*. The process is similar to, but distinct from, fluorescence where light is absorbed at one wavelength and emitted at another.

Light is measured by spectrographs as it is reflected off the surface of Mercury and as it is scattered by atoms in Mercury's exosphere (Figure 6.1). The measurement results in a spectrum in which the continuum, the depressions of the Fraunhofer lines, and the emission lines are present. The amount of photons emitted by the atoms in the exosphere is measured in units of Rayleighs (R). Sodium emits about 1 million photons per second in a 1 cm^2 column. This amount is called a mega-Rayleigh (MR).

A slight offset in wavelength from the peak of the emission line and the depth of the absorption lines is a result of Mercury moving relative to the Earth at the time of measurement, and, thus, its emitted light is shifted with respect to the wavelength of the solar feature. This shift is called a *Doppler shift*.

6.1.4 Exospheric pressure?

The pressure of the known exosphere is a few times 10^{-12} bar (b). This is ~1/1,000,000,000,000 the pressure of Earth's 1 bar atmosphere. Mercury's atmospheric atoms do not collide appreciably with one another, only with the planet surface. For this reason it is called a surface-bounded exosphere. Mercury's exosphere has multiple speed distributions with some, and perhaps all, species having multiple speed components that result from differing source, release, and recycling mechanisms.

6.1.5 New discoveries are likely

It is likely that NASA's *MESSENGER* mission (see Chapter 13) will make new exospheric discoveries with its atmospheric spectrograph (MASCS), because it analyzes the region from 1150–6000 Å with the ability to observe very faint resonance emissions above Mercury's surface.

Two gases of particular interest are sulfur (S) and hydroxide (OH). This is because ground-based very high-resolution radar imaging of Mercury's surface has revealed deposits at latitudes greater than ~70°N and S. The deposits are in permanently shadowed craters, thus remaining very cold over geologic periods of time (billions of years). These deposits have radar reflection and polarization characteristics that are similar to deposits of water ice on Mars and the *Galilean satellites*. However, this similarity could be caused by other substances, such as S, that are very transparent to radar signals at 7 and 35 cm (the wavelengths used in many radar studies). Other possibilities must also exist but are not presently known.

If the substance stored in the shadowed craters is water ice then it is possible that there will be a thin water vapor signature above the region. When photons break apart the water vapor molecule, disassociation of its two neutral components, OH and H occurs. While the H_2O cannot be observed directly, the H can be detected by a neutron mass spectrometer and the OH by an ultraviolet spectrometer. If these substances are both found by *MESSENGER*, or some other spacecraft like *Bepi Colombo*, then it will be excellent evidence that the stored volatiles are water ice.

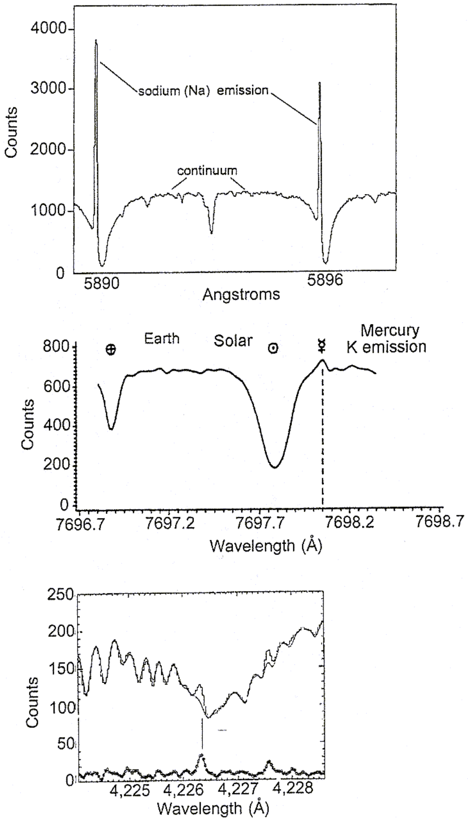

Figure 6.1. Actual spectra from Mercury's exosphere of sodium (Na) (top), potassium (K) (middle), and calcium (Ca) (bottom). In the spectrum of Na the sharp emission peaks at 5890 Å and 5896 Å are to the left of the Solar Fraunhofer absorptions. In this case there is a *blue-shift*. In the middle spectrum the small bump identified with the astronomical symbol for Mercury is the K emission line. For the K measurement there was a *red-shift*. A dotted vertical line below the emission peak guides the eye to the wavelength scale of the figure. The two dips in the spectrum are from Earth's atmospheric absorptions (marked with the Earth symbol ⊕) and an absorption caused by K in the Sun's atmosphere – the Solar Fraunhofer line (marked with the Solar symbol ⊙). Much more complicated is the spectrum from the wavelength region where Ca scatters light in Mercury's exosphere (bottom spectrum). The Fraunhofer absorption lines of Ca in the solar spectrum are wide and the many other absorptions are from other molecular absorptions in the Earth's atmosphere. The emission peak from Ca is denoted by a vertical line above (after continuum removal) and below (actual

If, however, emissions at 1636 Å (one of the wavelengths at which atomic S has its resonance scattering emissions) are found by the ultraviolet spectrometer, then it will be good evidence for S being the substance in the shadowed craters. Another possibility is that ordinary silicates that are low in iron may also give a radar backscatter signal when they are very cold. Thus, the radar bright spots may not be volatiles at all! Imaging, along with X-ray and γ-ray measurements, and measurements by the surface and atmospheric spectrographs may reveal that the mysterious radar signal is caused by some other, as yet unknown, substance.

6.2 EXOSPHERIC ATOMS AND MULTIPLE SPEED COMPONENTS

6.2.1 Collisions only with the surface

Because atoms in the exosphere do not collide with one another, the speed and direction of their motion is determined by the release mechanism from the surface, and the arrangement and character of the surface grains. Much effort has been spent to understand these physical issues. Some details are gleaned from measurements of the light emitted from the atoms and relevant physical laws. For H and He at least two populations, high and low temperature groups, were discovered as a result of modeling density and height profiles measured above the planet's surface by instruments on *Mariner 10*. Daylight and darkness each last about 88 Earth days on Mercury, and the surface, therefore, reaches extremes of temperature because the exosphere is too thin to modify the surface temperature as happens on Earth. The cold gas component results from atoms hopping from the night side and the smaller warmer component is formed on the day side. Helium extends from 3000–4000 km above the surface, and thus, was seen against the nightside of the planet and well off the sunlit side where solar photons were able to interact with He atoms.

6.2.2 Detection of Multiple Speed Components

For Na, detection of multiple speed components was possible because the width and shape of the resonant emission line measured with ground-based telescopes and spectrographs, could be modeled. The first such measurements of the Na emission line showed that the Na atoms had a most probable speed of ~600 m/s with an equivalent temperature of ~230°C. For comparison, the atoms and molecules in Earth's atmosphere have a most probable speed of about 350 m/s and at a temperature of about −3°C. The shape of the Mercury Na emission line also showed that a hotter population of atoms, perhaps up to ~1000 K, could be present. Later measurements did indeed exhibit characteristics of much warmer temperatures and higher speed atoms; different speeds being observed at the equator and in the polar regions (ranging from ~330°–1230°C).

For K, there are no measurements to date which can be used to discriminate multiple speed components in Mercury's exosphere. It is likely however, to also have atoms travelling at many different speeds. Ca was observed above and beyond the southern hemisphere of Mercury using a spectrograph and large telescope (Keck I) on Mauna Kea, Hawaii. The emission lines exhibit characteristics of high speed and high temperature (~12,000°C) atoms. The equivalent most probable speed for Ca is ~2.2 km/s. The speed at which an atom will escape Mercury's gravitational field if it is moving straight away from the center of the planet is called the *escape velocity*. The speed of Ca is thus considerably less than Mercury's escape velocity of 4.2 km/s. Thus, what Ca is present about the planet is still in the grip of the planet's gravitational force and not likely to be lost until it is ionized and then, having an electrically positive charge, it can be carried away in the electric fields of the solar wind.

6.2.3 Atoms in escape

Because of pressure from sunlight, some atoms are pushed far from Mercury's surface and beyond the gravitational force that keeps them bound to the planet. Therefore, some atoms escape from Mercury. On Earth, the escape velocity is 11 km/s which is more than twice that of Mercury. The amount of sunlight pressure varies considerably as Mercury moves around the Sun – both the distance to the Sun and the speed of Mercury's motion are changing.

Clever observations from Kitt Peak Observatory using the McMath Pierce solar telescope were able to image the escaping Na atoms at times of high *radiation pressure* on Mercury. One such image (Figure 6.2, see colour plate section) shows the coma of Na about the sunlit crescent and the tail streaming behind the planet. The observations were tailored towards measurement of the downstream profile of the tail along its axis. West is on the right, and south is at the top of the figure. The position of Mercury and the portion of the illuminated crescent is shown with the Na coma in front, above and below. The Na tail is seen streaming behind.

6.3 ATMOSPHERIC SOURCE, RELEASE, AND RECYCLING PROCESSES

The multiple speed distributions of atoms in the exosphere indicate that there are multiple physical processes at work to provide new atoms and to release recycled ones back to the exosphere. New sources are materials from volatilized meteorites, atoms from freshly exposed rock or buried sources, and a small component of Na, H, and He that come from the Sun delivered as ions in the solar wind. Recycled atoms are those that have been in the exosphere and subsequently have been stored on the surface for a period of time before being re-released from the surface back to the exosphere. Sunlight and ions from the solar wind strike atoms on the surface and release them back into the exosphere. Evaporation, or thermal desorption, is a major release process for H, He, Na, and K.

6.3.1 Differentiating one source from another

There is a decade-long history attempting to decipher telescopic data in terms of the sources, release mechanisms, and recycling processes. Much of the data can be interpreted in more than one way. For example, images of Na emission in Mercury's exosphere often show bright regions that appear at different locations from one measurement to the next. Some scientists believe that the bright emission spots are seen over Na rich rocks on the surface that have been freshly exposed by meteoritic bombardment. Other scientists believe that the same emission spots are caused by ions sputtering Na off of the surface as they are directed along electric fields associated with the magnetic field of the planet (Figure 6.3, see colour plate section).

More ground-based imaging and spectroscopy may be able to settle this issue. With systematic observations made with telescopes and imaging facilities with adequate pixel scale, it may be possible to determine if the bright spots always appear over fresh craters on the surface, or if they appear during times of active "space weather" from the Sun. Some examples of the ground-based observations we do have are shown in Figure 6.4 (see colour plate section). In this figure, the radar bright regions B (northern hemisphere) and A (southern hemisphere) are shown in all images. These regions appear bright in radar backscatter because the surfaces are rough at the tens of centimeters scale, probably because they are fresh impact craters and are surrounded by fresh blocks of crater ejecta. They are on the side of the planet not imaged by *Mariner 10*. Atmospheric emissions of Na and K have also been seen over the radar bright regions. In the recalibrated *Mariner 10* images the Kuiper Muraski crater complex appears as a very bright fresh region (represented by the letter K). The Caloris basin is also shown in the images of Figure 6.4 (represented by the letters CB). Enhanced Na and K (potassium) have been observed over Caloris Basin. These regions and atmospheric observations are shown in the nine panels of Figure 6.4 (see colour plate section).

6.3.2 Ions recycle back to the surface of Mercury in electric fields

As discussed in Chapter 5, the interplanetary magnetic field (IMF) is a source of ions in the vicinity of Mercury. Also ions created near Mercury by photolysis of atmospheric neutrals are controlled by the local electric fields. Such electric fields E, are created by charged particles moving with velocity V in the solar wind magnetic field B, as shown in Figure 6.5. It is possible that some of the Na and K enhancements are caused by emissions from neutral atoms that are created after Na^+ and K^+ strike Mercury's surface. Because the direction of fields in the IMF change periodically, this mechanism could account for some of the time variation observed in the Na and K emissions in the atmosphere.

6.3.3 Exosphere and surface link

Obviously the exosphere and surface are linked by the gas-surface interface – the place where collisions, storage, and release occurs. But, does the exospheric

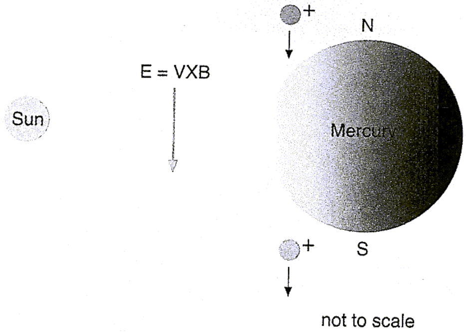

Figure 6.5. Na^+ and K^+ will interact in the electric fields in and around Mercury's magnetosphere and the IMF. Such ions will eventually be swept away into the interplanetary medium or will impact on Mercury's surface, become neutralized and eventually be recycled to the atmosphere unless they find a permanent cold trap. Mercury's magnetic field is not considered in the diagram. See text for explanation of E, V, and B.

composition reflect, in a significant way, the surface composition? It is of great importance to know if Mercury has more Na and K than is expected from our understanding of how planets form. Also important is whether Mercury ever had water, and if so how much? The study of the exosphere may help us answer these questions.