PERSPECTIVES: SOLAR SYSTEM SCIENCE

Two Bodies Are Better than One

Joseph A. Burns

In 1994, the Galileo spacecraft sighted the tiny moon Dactyl orbiting the asteroid 243 Ida (see panel A in the figure) (*1*). Since then, nearly 30 binaries have been found among the smaller bodies of our solar system (*2*). As more and more of these unusual objects are detected, they furnish densities for numerous asteroids and reveal how collisions have shaped the solar system.

Two centuries ago, William Herschel first pointed out a similar phenomenon among stars. Since then, observations of binary stars (*3*) have provided the foundation on which stellar astrophysics is built. Their orbital periods, combined with the separation between the stars, yield stellar masses and help to determine stellar radii, luminosities, and surface temperatures. Furthermore, binaries of different ages residing in various stellar nurseries provide insights into star formation and evolution. Might observations of solar-system binaries be as informative about the properties and origins of Earth's celestial neighbors?

Techniques similar to those used to identify double stars have been employed to discover their closer cousins. Solar-system binaries are, however, generally more difficult to detect than stellar ones because angular separations are often smaller, brightness differences between components can be much greater, and solar-system binaries are much rarer, both in relative and in absolute terms. Short orbital periods of days rather than years ease the task somewhat.

Solar-system binaries have been detected with ground-based telescopes (see panel B of the figure) (*4–6*), and with the Hubble Space Telescope (*7*). Periodic brightness variations (*8*), caused by individual components eclipsing and occulting one another, may indicate duplicity. In addition, radar (panel C) (*9*) can discriminate double asteroids nearby, and spacecraft flybys (panel A) (*1*) of asteroids might sight targets. Because all these methods have strong detection biases, any apparent trends among tabulated binaries must be interpreted cautiously.

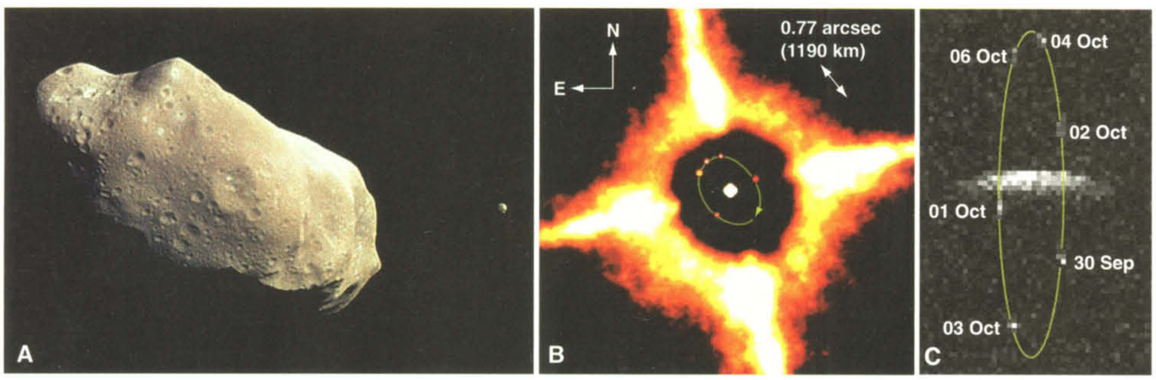
Various creation and destruction mechanisms (*2*, *10*) compete to produce the extremely diverse extant binary population. Pairs can be born during nebular collapse at the time of the solar system's origin (similar to binary stars), or when tides yank material off the surface [comet Shoemaker-Levy 9 is the archetype (*11*)], or through collisions (as Earth-Moon and Pluto-Charon demonstrate).

Breakup can occur during close passage of a planet when tides and rotational spin-up lead to mass-shedding of loosely bound material (*12*). Impacts into an asteroid can also cause rotational fission into two bodies, but this often does not happen because sufficient angular momentum cannot be transferred without simultaneously demolishing the target and scattering the debris (*13*). After a collision, impact ejecta will usually depart in the direction of the primary's final spin. For escaping clumps to be trapped on bound orbits, energy must be lost, for example, through gas interactions, jostling, nonspherical gravity, or solar effects (*13*).

Binaries can be destroyed (*2*, *10*) when impacts shatter a small satellite or disrupt the system entirely. The mean collisional lifetimes (*14*) of small asteroidal satellites are less than the solar system's age, indicating that they are still being formed. Orbits become unstable if an irregularly shaped primary is approached too closely by its satellite (*15*) or if binary objects are too distant (*16*). Binaries that pass planets within a few radii are also disrupted (*12*).

To date, telescopic searches have found satellites around eight main-belt asteroids (the minor planets that reside between the orbits of Mars and Jupiter), indicating that about 1 to 2% have companions. This technique will not, however, identify small, dark, or close satellites. Almost all the primaries among these pairs spin rapidly (4 to 6 hours) and display significant brightness variations, implying very nonspherical shapes. Satellites generally move within a dozen radii of the primary, and are usually very small (typically one-tenth of the primary's size in diameter). Only one of these binaries, 90 Antiope, has similar-sized components.

The three satellites with known directions of orbital motions advance in the same sense as their primaries spin. Formation by reaccretion of cratering ejecta (*13*), following an impact, seems plausible for this class. Because collisions are believed to produce most binaries, and asteroid families are the end result of catastrophic collisions, family members should preferentially be binaries. Yet this is not observed.



Solar-system binaries. (**A**) Galileo spacecraft image of Ida and its small moon Dactyl (*1*). (**B**) 45 Eugenia's moon Petit Prince seen in the infrared with adaptive optics at 5 epochs. The primary's brightness has been suppressed. The "cross" is an artifact (*2*, *5*). (**C**) Delay-Doppler radar images of 2000 DP107. The dashed line shows the companion's approximate trajectory during 7 days (*2*, *9*).

CREDIT: PANEL A FROM (1), PANEL B ADAPTED FROM (5), PANEL C ADAPTED FROM (9)

Radar and light-curve inversions have identified about a dozen binaries around near-Earth asteroids (NEAs)—escapees from the main belt whose orbits do or will cross Earth's orbit. About one in six NEAs (*8*, *9*) is binary, in agreement with the fraction of double craters on the terrestrial planets being bombarded by the NEAs (*17*). Like virtually all NEAs, most primaries in NEA binaries are small (about a kilometer in radius), with even tinier satellites, typically only one-fourth to one-half as large in di-

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ameter. Radar studies have shown that the primaries usually spin in ~2 hours, near the spin period at which a cohesionless body can no longer be held together by gravity; are roughly spherical; and have low—albeit poorly constrained—densities. Orbits are almost circular and close (~5 primary radii). Because NEAs are more often binaries than other objects and traverse planetary orbits, the suspicion is that they formed when fragile rubble piles were tidally torn asunder (*12*), like comet Shoemaker-Levy 9 (*11*).

In the outer solar system, a satellite circles 617 Patroclus, one of six Trojans (the asteroids that orbit at Jupiter's distance) surveyed so far with adaptive optics. Seven trans-Neptunian objects (TNOs, residents of the Kuiper Belt or Centaurs), reflecting perhaps 1% of the TNO population, are binary (*2*). These outer solar-system binaries are distinctly different from those closer to the Sun, implying alternative formation mechanisms. The companions have comparable masses on eccentric, widely separated orbits. It remains unclear how such loosely bound objects can be formed. They may have been produced in the early solar system, when TNOs were more numerous.

Well-determined masses and shapes allow reliable estimates of density. Compared to the measured densities of carbonaceous (2.3 to 2.8 g/cm^3), stony (3 to 4 g/cm^3), or iron (5 to 6 g/cm^3) meteorites (*12*, *18*), asteroids (the putative source of meteorites) have remarkably low densities. For example, the main-belt asteroid 45 Eugenia's density is 1.2 (+0.6/-0.2) g/cm^3 (*2*), that of the NEA 2000UG11 is ~1.0 ± 0.5 g/cm^3 (*19*), and even the density of the "metallic" 22 Kalliope is just 2.3 ± 0.4 g/cm^3 (*2*). These low densities confirm estimates from spacecraft flybys and from direct gravitational tugs of other bodies. Asteroids must therefore contain significant pore space (40 to 60%) (*18*), suggesting an unconsolidated rubble-pile structure, as inferred from rotational studies (*20*).

As the mutual orbits of more solar-system binaries are tracked, we will be able to use the densities of the solar system's smallest members to understand their origins. Along with asteroid families, binaries are providing a code book to decipher the pivotal role of impacts in forming and destroying solar-system bodies. Like stellar binaries, solar-system pairs are revealing much about the processes that have given us today's rich world.

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PERSPECTIVES: LASER CHEMISTRY

Water Vapor Gets Excited

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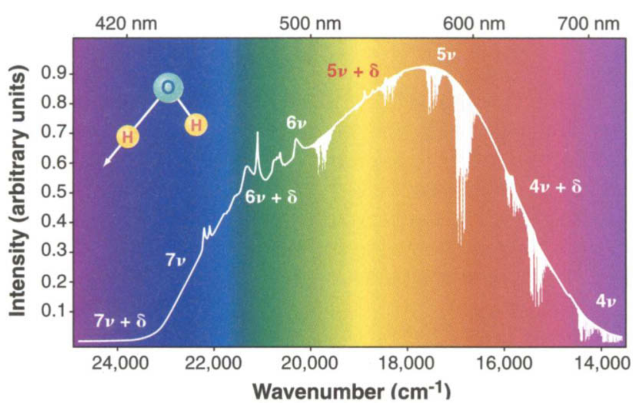
Water vapor is by far the most important greenhouse gas. By absorbing outgoing thermal radiation from Earth, it provides some 30 K of heating (*1*). Water vapor also absorbs about 10 to 20% of incoming solar radiation (*2*). The weak overtone bands of water (see the figure) play an important role in this absorption because the solar photon flux peaks at ~630 nm, in the yellow-red part of the visible spectrum. Both the amount of water vapor in our atmosphere and the strength and position of its absorption bands thus help to maintain Earth's energy balance (*1*).

The intensities of the absorption lines are determined by the electric dipole moment surface, which describes the charge distribution in the water molecule as a function of the two O–H bond lengths and the bond angle. A reliable dipole moment surface is thus essential for the calculation of a molecular spectrum from first principles. Several dipole moment surfaces are available for water (*3*, *4*). On page 993 of this issue, Callegari *et al.* (*5*) report a clever method for testing their quality.

The prediction of the water spectrum on the basis of ab initio potentials and dipole moment surfaces is very important. Currently available experimental data cannot account for the atmospheric absorption of sunlight (*6*). In astronomy, the spectral energy distribution emitted from cool stars and brown dwarfs is strongly modulated by water absorption (*7*), which cannot be simulated with existing experimental data. Only theory can generate the many millions of weak absorption lines that are required to bring observations and simulations into agreement (*8*). Ab initio predictions of the water spectra have also been used to assign hot water spectra in sources such as sunspots (*9*).

The prediction of an absorption spectrum requires as minimum input a set of line positions, their intensities, and a lineshape function. Often these data are derived from experiment and tabulated in public databases (*10*). Water line positions can routinely be measured to eight significant digits, whereas line intensities typically have an accuracy of only 5%. Hence, empirical dipole moment surfaces deduced from experimental data have modest reliability (*4*). Dipole moment surfaces derived from state-of-the-art ab initio calculations (*5*) are probably more accurate.

What molecular properties of water determine the positions and strengths of the absorption lines? From a theoretical perspective, the line positions are determined by the changes in the total electronic energy as a function of the two OH bond lengths and the bond angle, captured in the potential energy surface (*11*). Simi-



Now you see it. The visible absorption spectrum of water, recorded with a high-resolution Fourier transform spectrometer and a long-path absorption cell. The overtones are the small modulations of the spectrum. **(Inset)** The water overtone O–H stretch. [Adapted from (*15*)]

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