ment's 20-kilogauss axial magnetic field. With the aid of this axial field—eschewed by the Livermore experiment—the group was able to amplify a 7-kW input radiation pulse to 17 MW with an electron beam energy of only 0.9 MeV, just about the same 34-dB gain achieved a few months later at Livermore.

The NRL group, including participants from the Universities of Utah and Maryland, took its 600-amp electron beam from a pulse-line accelerator—essentially a single-shot device coupled to a large capacitor bank through a pulse-forming transmission line. The extraction efficiency with which energy was transferred from the electron beam to the radiation was observed to be about 3.2%.

Like the Livermore–Berkeley collaboration, the NRL group has achieved even higher gain levels with lower-power radiation input (subsaturation signals) and, indeed, with no radiation input at all ("superradiant" experiments). In these superradiant experiments, one begins not with input from a magnetron tube, but rather "from noise." As the electron beam undulates between the alternating-polarity magnet poles of the wiggler, it emits incoherent synchrotron radiation with a broad spectrum that peaks at the wavelength at which the FEL will eventually lase. This incoherent noise is sufficient to get the process of coherent laser amplification started even in the absence of radiation input or reflectors. In such superradiant experiments, however, it is more difficult to pin down the performance characteristics of the FEL system.

Gold stresses the potential usefulness of free-electron lasers as broadband high-power amplifiers in the millimeter-wave regime. Although conventional microwave generators such as klystrons, magnetrons and traveling-wave tubes can put out very high power levels at wavelengths near 30 cm, this power falls off rapidly with decreasing wavelength. Gyrotron tubes, Gold suggests, could in principle be designed to deliver high pulsed power efficiently at wavelengths below a centimeter, but to date they have served primarily as narrow-band amplifiers or fixed-frequency oscillators. For fusion-plasma heating with millimeter-wave radiation, for example, a Gyrotron oscillator would be the FEL's principal competitor.

The great virtue of the free-electron laser at these wavelengths, aside from its tunability, Gold suggests, is its broad bandwidth. "Without turning a knob," he told us, "one can amplify millimeter-wave signals containing a very wide spectrum of frequencies. "This would be particularly useful for radar and communications," he argues. One would shape a desired signal waveform on a low-power device and then amplify it to very high power with a free-electron laser.

"With its axial magnetic field, our experiment is principally relevant for high-power microwave and millimeter-wave applications," Gold explains. The Livermore–Berkeley experiment, on the other hand, looks primarily toward extrapolation to much shorter wavelengths. Another FEL group at NRL, led by John Pasour, has been using an old National Bureau of Standards induction linac to do superradiant experiments[3] at a wavelength of 1 cm. Because their induction linac has much longer beam pulse lengths (2 μsec) than the other groups, Pasour and his colleagues are looking toward the possibility of a free-standing high-power microwave laser oscillator. —BMS

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Stellar companion appears to be giant planet

Is Jupiter as large as a planet can be? Are the Sun's faint neighbors, with roughly 10% of its mass, the smallest stars? There is no apparent physical reason that objects in the mass range of 5 to 50 times the mass of Jupiter should not exist, and although the properties of such objects have not been well explored theoretically, their existence has important implications for a number of fields in physics and astronomy.

Now astronomers at the University of Arizona (Steward Observatory) and the Kitt Peak National Observatory have identified a companion to a nearby star named VB8 that appears to have a mass in this range—a mass below that at which hydrogen fusion reactions can occur in its core. In a paper published in the March issue of the *Astrophysical Journal*, David McCarthy (Arizona), Ronald Probst (Kitt Peak) and Frank Low (Arizona) argue[1] that they have identified a "substellar brown dwarf," or, to those uninitiated into astronomical jargon, a planet.

The existence of planetary systems beyond our own has been a topic of speculation for at least four centuries, since Copernicus displaced the Earth from its central position in the universe. Systematic searches have been conducted for nearly 100 years, using the techniques of classical astrometry to obtain precise positions for the nearby stars and then to follow their motions across the sky over several decades in an attempt to detect periodic deviations from a rectilinear trajectory caused by orbital motion about a stellar–planetary barycenter. In 1962, Peter van de Kamp of the Sproul Observatory published data indicating that Barnard's star (one of the ten nearest stars to the Sun, at a distance of 6 light-years) exhibited such motion, suggesting a companion with a mass several times that of Jupiter in a highly eccentric orbit. Subsequent work by several other astrometrists casts serious doubt on this claim, although a few additional examples of such nonlinear motion were subsequently uncovered.

One of the largest currently active astrometric programs is conducted by the US Naval Observatory with its 61-inch telescope at Flagstaff, Arizona. One of the Naval Observatory's major activities consists of determining the distances of some 1000 nearby stars using trigonometric parallax (observing the displacement of these foreground objects against the background of distant, fixed stars as the Earth describes its annual solar orbit). The stars for this program were selected as exhibiting large secular angular displacements on photographic plates taken several decades apart (which, for the relatively narrow range of intrinsic stellar velocities, implies relative proximity to the Earth). Robert Harrington (USNO) told us that VB8 was added to this program a decade ago, and that within a few years it showed a scatter about the expected parallactic curve that was larger than that of other program stars. Only about a dozen of the 1000 stars being monitored showed such deviations. Harrington and his collaborators drew attention to the possibility of a companion for VB8 about two years ago.

McCarthy and Low, meanwhile, have been interested in developing high angular resolution techniques for use in infrared astronomy for nearly a decade. The most promising of several methods to emerge was an adaptation of a technique employed for some time by optical astronomers: speckle interferometry. The image size of stars recorded by ground-based telescopes is determined principally by the amount of refraction—from turbulent cells in the atmosphere—suffered by the incoming plane wave, rather than by the diffraction limit of the telescope. The speckle observer circumvents this limitation by recording a series of rapid exposures with a separation short compared to the characteristic timescale of changes in the turbulent cells above the telescope. Each "speckle image" contains the total light divided among numerous, slightly displaced, diffraction-limited subimages. Computing the power spectrum of this image by Fourier transformation, one recovers the high spatial frequencies partially, although the phase information needed to construct a true image is lost.

The difficulty in applying this technique in infrared astronomy is that, until very recently, only single-element detectors (as opposed to array detectors or photographic film) were available to record the incoming signal. The Arizona group (as well as other groups; see PHYSICS TODAY, May 1984, page 17) have overcome this limitation by placing a slit in the telescope's optical path in front of the detector and then sweeping the image back and forth along the slit by driving the telescope's secondary mirror. Observing at the National Optical Astronomy Observatory's 3.7-m telescope and the Steward Observatory's 90-inch instrument on Kitt Peak, the group uses a 70-arcsec/second sweep rate while recording the signal at wavelengths of 1.6 and 2.2 microns. The bandwidth of the detector output covers spatial frequencies from essentially 0 to 8.4 cycles/arcsec. Each scan is Fourier analyzed by an on-line microcomputer while the raw data is simultaneously recorded for later analysis. A typical run consists of 10^4 scans yielding 10^4 power spectra representing the transform of the amplitude of the true sky brightness distribution; the loss of the phase information results in a 180° ambiguity in the location of two closely spaced objects.

To calibrate the transfer function of the atmosphere and the telescope, a standard (presumably point-like) star is chosen close to the target object. A typical run consists of 600 scans on the target star followed by 600 scans of the standard; low-frequency variations in atmospheric conditions are removed by normalizing the power spectra derived from each block of target observations to those of the standard.

While this technique is being developed to study objects with complicated surface-brightness variations—such as asteroids, the moons of Jupiter, star formation regions and the nuclei of active galaxies—McCarthy has been working for the past three years on applying ir speckle interferometry to the study of nearby stars with proposed astrometric companions, both as a test of the method on relatively simple brightness profiles and for the intrinsic interest that the confirmation of such companions would provide. Because slow changes in the atmosphere limit the dynamic range of the technique to two objects differing by no more than a factor of 40 in infrared brightness, he compiled a list of the faintest, reddest stars that appeared on lists published by the various astrometric observatories as candidate binary systems. By observing only systems with faint primaries, McCarthy is sensitive to the faintest (and, most probably, lowest-mass) companions, and by choosing red objects, he is optimizing for signal-to-noise in his infrared detectors.

To date, McCarthy has results[3] for some two dozen candidate binaries, which divide into three categories. Most of these systems simply contain two stars—"star" is defined here as an object that, at some point in its evolution, generates all of its radiated energy from hydrogen fusion. The current theoretical lower limit is 0.08 solar masses, or about 80 times the mass of Jupiter ($80M_{♃}$). Another 5 or 6 candidate binaries show no evidence of a companion in the speckle images; however, because several of these have masses, estimated from the astrometry to be approximately $20M_{♃}$ and would be expected to contribute very little optical/ir light, this is hardly surprising.

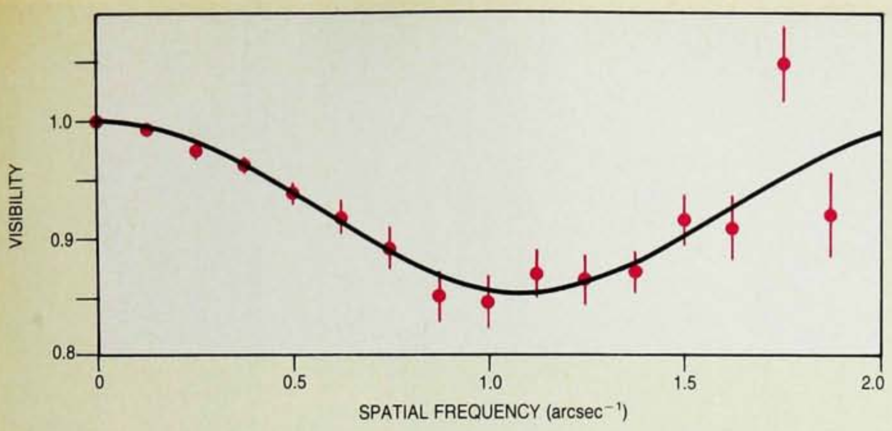
Seeing a substellar companion. The third category of results has but a single member—VB8—which is described in the recent paper.[1] The spatial frequency visibility curve at 2.2 microns (figure 1) clearly indicates a close fit to the model light distribution for a binary system. An initial estimate of the mass from the published astrometric data (which yielded a suggested orbital period of about 60 years) and the linear separation of the two stars (derived from the speckle image) lie in the range $10M_{♃}$ to $80M_{♃}$. At a paper given by Harrington and his collaborators at the March meeting of the American Astronomical Society's Dynamical Astronomy Division in Austin, the astrometrists claim to narrow the range to 20–$60M_{♃}$, as well as to resolve the 180° ambiguity in the position of the two stars inherent in the speckle technique.

McCarthy offers two additional arguments for a substellar mass of VB8B, as the new companion to VB8 is called. First, its absolute brightness as measured at 2 microns is a factor 25 lower than that of the companion of another nearby star—Ross 614B—which, with an accurately measured mass of $80M_{♃}$, is thought to be just at the dividing line between stellar and substellar objects ($80M_{♃}$). Finally, an effective temperature determination from the 1.6- and 2.2-micron data yields a value of $T = 1360$ K and a total luminosity of 3×10^{-5} times that of the Sun, significantly below those expected theoretically for a stellar source. Thus, as McCarthy and his colleagues conclude, the neighboring source to VB8 is "consistent with [being] a substellar mass companion—i.e., a planet."

As McCarthy and his colleagues note in their introduction, the observation of substellar mass objects is of considerable interest to a number of fields in current astrophysical research, including the "missing mass" problem, planet formation, and even the demise of the dinosaurs. John Bahcall of the Institute for Advanced Study has written extensively on the first of these issues and is delighted by the brown-dwarf detection. In addition to the many interesting astrophysical implications, he views the discovery as "a clear assignment for physicists to do their homework on this very interesting class of objects." The equation of state for matter at the densities and pressures characteristic of the interior of such objects is poorly understood; for example, the densities are high enough that Coulomb corrections and interpenetration by atoms become important, and an accurate mass–radius relation is unavailable.

Another important unknown is the brown-dwarf cooling rate, for which one requires accurate estimates of the radiative opacity throughout the star, particularly in the atmosphere, which is cool enough for molecules to form. Jill Tarter of the NASA-Ames Research Center, who published some of the earliest cooling calculations for brown dwarfs, said of the equation-of-state problem: "The answer may lie at Livermore," where the expertise for studying the physics of matter at these temperatures and densities, as well as the ability to handle problems of this computational complexity, are to be found. However, the Livermore codes were not designed for this specific problem, and substantial work remains before quantitative new results can be expected.

The form of the cooling curves turns out to be an important factor in estimating the mass of the newly found object. In addition to Tarter's decade-old calculation, there was but one other serious attempt to estimate the rate at which very low-mass stars and substellar objects radiate their gravitational potential energy. Those results, published[4] by David Stephenson, now professor of planetary science at Caltech, are qualitatively similar to the earlier calculations although they differ in significant quantitative detail. The Tarter results suggest a mass range for the observed companion to VB8 of 30–$40M_{♃}$, while the Stephenson calculations, which find a more gradual cooling rate for such objects, allow masses



The visibility function (amplitude vs. spatial frequency) of the star VB8, measured[1] by McCarthy, Probst and Low in the east–west direction at a wavelength of 2.2 microns, using infrared speckle interferometry at the NOAO 4-meter telescope on Kitt Peak. The fitted curve is the visibility function expected for a binary star system.

ranging from 30 to $80M_{♃}$—perilously close to the limit for the onset of fusion.

In a much more recent paper, just submitted to the *Astrophysical Journal*, two Italian theorists, F. D'Antona and I. Mazzitelli, present new cooling curves for objects less massive than $0.1M_{\odot}$, which may further complicate the interpretation of the VB8B source. By using a significantly larger opacity than that assumed in earlier work, these authors suggest that 80–100-$M_{♃}$ stars take as much as an order of magnitude longer to reach fusion ignition than previously thought. Because these stars would then radiate their gravitational potential much more slowly than in previous scenarios, they may have luminosities as low as a substellar object for a long pre-ignition period. The result is an ambiguity for an object with the luminosity of VB8B; it could either be a relatively young 50-$M_{♃}$ substellar object or a 5-billion-year-old 0.08-$M_{\odot}$ star that has yet to initiate core fusion. Tarter points out that the increased opacity of these new calculations derives from the assumption that a significant quantity of grain material exists in the photospheres of the objects. Because grains are found neither in the atmosphere of Jupiter nor in the outer layers of the least massive stars, this assumption is clearly open to question. However, the overall uncertainty in the cooling rates for masses below $0.1M_{\odot}$ is but one example of the lack of detailed theoretical models for these objects, a situation which the detection of VB8B is likely to rectify in the years ahead.

McCarthy's collaborator, Probst, is now searching for examples of isolated brown dwarfs—as he points out "those that occur in binaries don't begin to make a dent in the missing mass problem." The difficulty with such searches is that they must rely for candidate objects on proper motion surveys carried out in the visible band, where even nearby objects with temperatures less than 1500 K may fall below the detection threshold. Candidate objects are, of course, much brighter in the ir band, but here the field of view for a search is extremely limited. Imaging array detectors in the infrared are just now becoming available for use in astronomy, but they can still sample only a tiny fraction of the area (a few square arcminutes) covered by a 14-inch photograph plate (about 35 square degrees), making ground-based ir surveys impractical. The brown-dwarf space density required to make up the local mass deficit found[5] by Bahcall and his collaborators is 2 to 3 times the normal star density. However, the implied *surface* density of such objects out to a distance of, say, 30 light-years (within which 1000-K objects could be readily detected) is only 1 per 50 square degrees.

IRAS. There now exists one all-sky survey at ir wavelengths: that conducted during 1983 by the Infrared Astronomy Satellite (PHYSICS TODAY, May 1984, page 17). Data were collected in each of four wavelength bands centered at 12, 25, 60 and 100 microns. The angular resolution of the survey is only an arcminute, so the detection of nearby stars through astrometric techniques is excluded. However, as Frank Low, McCarthy's other collaborator, pointed out, one of the original motivations for IRAS was to search for nearby brown dwarfs and Jupiters; and while the 12-micron sensitivity of the experiment was a factor of 5 too low to detect a 1-$M_{♃}$ object at interstellar distances, it was sufficient to see an object with the temperature and luminosity of VB8B out to several light-years. Thus Low posits that there may well be a few such dwarfs lurking amongst the nearly 200 000 sources in the IRAS catalog, and he has activated what he calls the "needle-in-the-haystack algorithm" to find them. This search method consists of attempting to identify each IRAS source with a counterpart on the archival plates of the National Geographic–Palomar Observatory and European Southern Observatory optical sky surveys. Any source not so identified becomes a potential candidate for followup ground-based ir photometry. A first pass through a small region of the sky near the galactic pole yielded an identification for every IRAS source, but Low is undaunted. By summer his group expects to have a preliminary result: Either they will be able to set a significant limit on the space density of such objects, or they will say "here is one." A useful byproduct of this work is that the IRAS team is digging deeper into the 12-micron survey data and will produce a map with three to four times the sensitivity of the published source catalog.

While McCarthy intends to continue his ground-based program to find planetary companions to nearby stars, the next major step forward in this field will most likely come in space. NASA's next major infrared mission, the Space Infrared Telescope Facility, will have a 0.8-m cooled telescope with detectors capable of seeing a Jupiter at the distance of Barnard's star in a 3-second integration. While this remarkable sensitivity will not be available until some time in the next decade, the Hubble Space Telescope, due for launch late next year, could make a significant contribution to the search for brown drawfs in the solar neighborhood. Space Telescope's 2.4-m mirror is uncooled, limiting observations to wavelengths shorter than about 3 microns, and the current instrument payload has no sensitivity to wavelengths longer than 9000 Å. An infrared camera will surely be proposed in response to the current announcement of opportunity for second-generation Space Telescope instruments, but Bahcall thinks that even the current payload can make a contribution. For example, he notes that if brown dwarfs indeed form the dominant component of the missing mass in the galaxy's disk, 100 Wide-Field Camera fields should turn up a few objects at $50M_{♃}$. The addition of an ir camera would extend such a search to $10M_{♃}$ objects at considerably greater distance.

—DAVID HELFAND

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