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DIRECT INFRARED IMAGING OF VB 8

M. F. SKRUTSKIE[1]
Department of Astronomy, Cornell University
AND
W. J. FORREST[1] AND M. A. SHURE[1]
Department of Physics and Astronomy, University of Rochester
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ABSTRACT

Near-infrared images of VB 8 taken at K (2.2 μm) and L' (3.75 μm) during a period of good seeing at the IRTF show no evidence of the brown dwarf companion reported by McCarthy, Probst, and Low in 1985. Any companion 1″.0 away from the primary must be at least 4 mag fainter than the primary at K and 3 mag fainter at L' in order to escape detection. A faint nebula centered on the star with scattering properties similar to a nebula detected near another main-sequence M star, Lalande 21185 (reported by McCarthy in 1986), may account for the extended emission detected by speckle observations.

Subject headings: infrared: general — stars: individual

I. INTRODUCTION

Van Biesbroeck 8 is one of the faintest, least massive main-sequence stars known. Interest in this object increased with the discovery that it may not be a point source. Speckle interferometric observations by McCarthy, Probst, and Low (1985, hereafter MPL) resulted in visibility functions that consistently deviated from unity in both the H (1.6 μm) and K (2.2 μm) photometric bands. MPL suggest that these deviations result from a binary substellar companion based on the color temperature and particularly on the observation that the visibility function rises toward unity again at higher spatial frequencies rather than monotonically decreasing. If this interpretation is correct, the visibilities are consistent with a companion, VB 8B, 3 mag fainter than VB 8 at K, 1″.0 away, with a temperature of 1360 K and a luminosity of 3×10^{-5} $L_{\odot}$. However, VB 8 is quite faint for infrared speckle interferometry, and the critical region of the visibility function for establishing binary structure lies at higher spatial frequencies where the data become noisy.

Direct imaging, though insensitive to spatial scales less than the seeing disk, profits from greater sensitivity than one-dimensional infrared speckle interferometry since at any instant all of the light from the source falls on the detector. Although the reported separation of 1″.0 is quite small, the magnitude difference is not so great as to exclude the possibility of directly imaging a cool companion in the infrared during a period of excellent astronomical seeing. Visual seeing of less than 1″ is not uncommon on Mauna Kea and improves at longer wavelengths. This *Letter* reports the results of direct imaging of VB 8 at K (2.2 μm) and L' (3.75 μm) with an infrared CCD array at the IRTF.

[1]Visiting Astronomer at the Infrared Telescope Facility, which is operated by the University of Hawaii under contract from the National Aeronautics and Space Administration.

II. OBSERVATIONS

Observations were made at the NASA IRTF 3.0 m telescope on Mauna Kea on the night of 1985 July 28 during a period of sub-arcsecond seeing. The Rochester 32 × 32 InSb infrared CCD array camera (Forrest *et al.* 1985) provided images of VB 8 and a nearby comparison star, 20 Oph (BS 6243, F7 IV, $m_v = 4.64$, 2°.6 from VB 8), at a scale of 0″.43 per pixel through 2.2 μm (K) and 3.75 μm (L') interference filters. Although 20 Oph is a spectroscopic binary, it is unresolved by visible speckle interferometry, and radial velocity measurements suggest an apparent separation of < 0″.05.

Short exposures minimize the effects of telescope motion and seeing on image quality. However, for an integrating detector, the signal-to-noise ratio increases for longer exposures. Therefore, a compromise exposure length of 5 s was chosen for all the images. For the 5 s exposures, the IRTF telescope gave superior images in its manual track mode (as opposed to computer track mode). The manual track mode, however, resulted in some long-term telescope drift, mostly in the direction of right ascension. During a typical series of eight 5 s exposures, the telescope would drift by roughly 1 pixel (0″.4). In addition to the steady drift, there were random motions of ~ 0.2 pixels between adjacent images, which could be due to telescope motions or seeing.

The sequence of 5 s exposures was as follows: eight of 20 Oph at K followed by 12 of VB 8 at K and 18 at L', followed by eight of 20 Oph at L' and eight at K. The signal-to-noise ratio of the peak pixel in a single 5 s exposure on VB 8 was 200 at K and 30 at L'. 20 Oph is approximately 5 mag brighter than VB 8 at both K and L'.

Within each of the above sets of integrations groups of four consecutive exposures were centroided, shifted, expanded by linear interpolation to a 63 × 63 grid, and summed. The rms diameter gives a measure of the size of the resulting images. The rms image size is twice the square root of the second

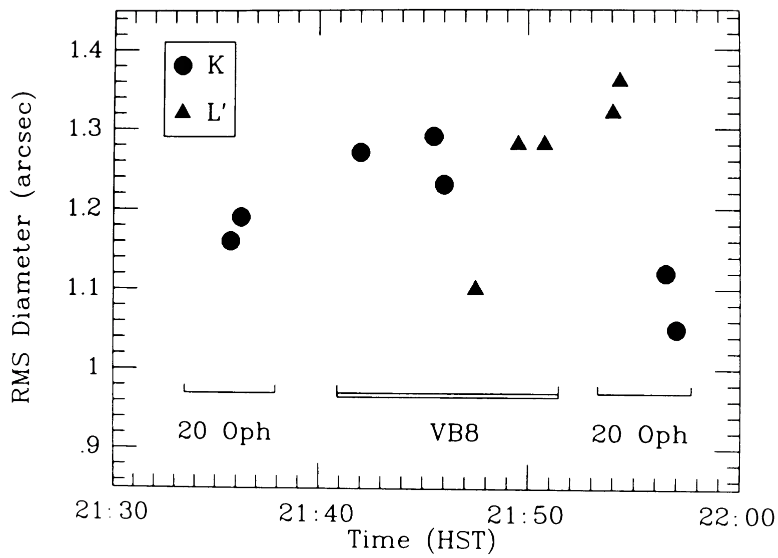

FIG. 1.—Root mean square diameters of the composite images vs. time (Hawaiian Standard Time) at K (2.23 μm) and L' (3.75 μm) for 20 Oph and VB 8 on the night of 1985 July 28. Each symbol represents a shifted-and-added composite of four 5 s integrations, except for L' images of VB 8 which represent sets of six integrations. The rms diameters were calculated in a 3″.2 octagonal aperture.

moment of the light distribution about the centroid. Figure 1 summarizes the rms sizes of the images versus time, wavelength, and object. For reference, a composite VB 8 K image with a rms diameter of 1″.3 had a FWHM diameter of ~ 0″.8, and the individual 5 s exposures were ~ 0″.64 FWHM.

Figure 2a (Plate L5) compares images of 20 Oph and VB 8 at 2.2 μm. The 20 Oph image is a composite of the last four 5 s exposures. It has a FWHM of about 0″.65, and, at a distance of 1″ from the star, the signal is 1% of the peak or 5 mag dimmer. The companion to VB 8 proposed by MPL is 3 mag dimmer and 1″ away. Thus the image quality achieved at the IRTF is well suited to searches for this companion. A similar shifted-and-added sum of four 5 s exposures of VB 8 is also shown in Figure 2a. The image is subtly larger, reflecting the generally larger images of VB 8 at 2.2 μm summarized in Figure 1, but no companion is evident.

Subtracting scaled images of 20 Oph, which represent our point spread function, from images of VB 8 permits a much more sensitive search for a stellar companion. Each of the individual 5 s exposures differed due to object motion on the array. Our pixel spacing of 0″.43 was only barely adequate for sampling these images, which were typically 0″.5–0″.65 FWHM. Comparing individual 5 s images, rather than the shifted-and-added composites, was the most successful method for removal of the point-spread function at K. For each of the 12 VB 8 5 s images, the list of 16 20 Oph 5 s images was searched for the closest possible match in the centroid of light, modulo integral pixel numbers. A few VB 8 images had more than one match, producing a total of 16 pairs from the original 12 images. Of these 16 matches eight included 20 Oph images taken before the VB 8 exposures and eight after. An octagonal aperture of diameter 2″.2 (5 pixels) for centroiding minimized the extent to which a nearby companion would bias the centroid. In most cases, a match of only 0.1 pixel shift in each coordinate could be found—for instance VB 8 at (row, column) = (21.7, 19.8) compared to 20 Oph at (20.8, 17.7) differ by 0.1 pixel in columns and rows. The sharper of the two images, i.e., closer to integral rows and columns, was shifted by linear interpolation to match the other exactly. This was done to match image sharpness as well as position. In the above example, VB 8 would be shifted 0.1 column to (21.7, 19.7) and 20 Oph would be shifted 0.1 row to (20.7, 17.7). Then the 20 Oph image was scaled so that its maximum pixel equalled the maximum in the VB 8 image, shifted by integral pixels, and subtracted. In general, there was a residual signal surrounding the zero pixel near the star center. The sum of 16 of these point-source–subtracted images produce the residual signal shown in Figure 2b. Each image was weighted inversely proportional to the amount of image shift—the weights ranged from 1 to 4. The apparent nebula shown in Figure 2b contains approximately 20% of the light of VB 8. Using the same 16 point-source–subtracted images but weighting each equally gave a similar appearing nebula with 17% of VB 8's light. As discussed later, this nebula may be real. In any case, the nebula is sufficiently faint to easily reveal a companion as described by MPL.

Figure 2c shows the nebula with a false star, 3 mag dimmer than VB 8, 1″ away at P.A. 27°. The false star is the image of 20 Oph shown in Figure 2a shifted, scaled, and added directly to Figure 2b, the sum of subtracted images. Adding the false star to each image in advance of the subtraction would have shifted the centroids by no more than 0.1 pixel. Such a shift would not adversely affect the search for a companion 1″ away. The signal-to-noise ratio is greater than 40 for the brightest pixel of the artificial companion, based on the fluctuations in the peripheries of this image. Figure 2b would easily reveal a companion of this brightness and separation. We found that a false star one-half as bright as the one in Figure 2c is still definitely visible, but one one-fourth as bright is lost in the nebular glow 1″ from VB 8. We conclude that any companion 1″ away from VB 8 would have to be at least 4 mag dimmer than the primary at 2.2 μm.

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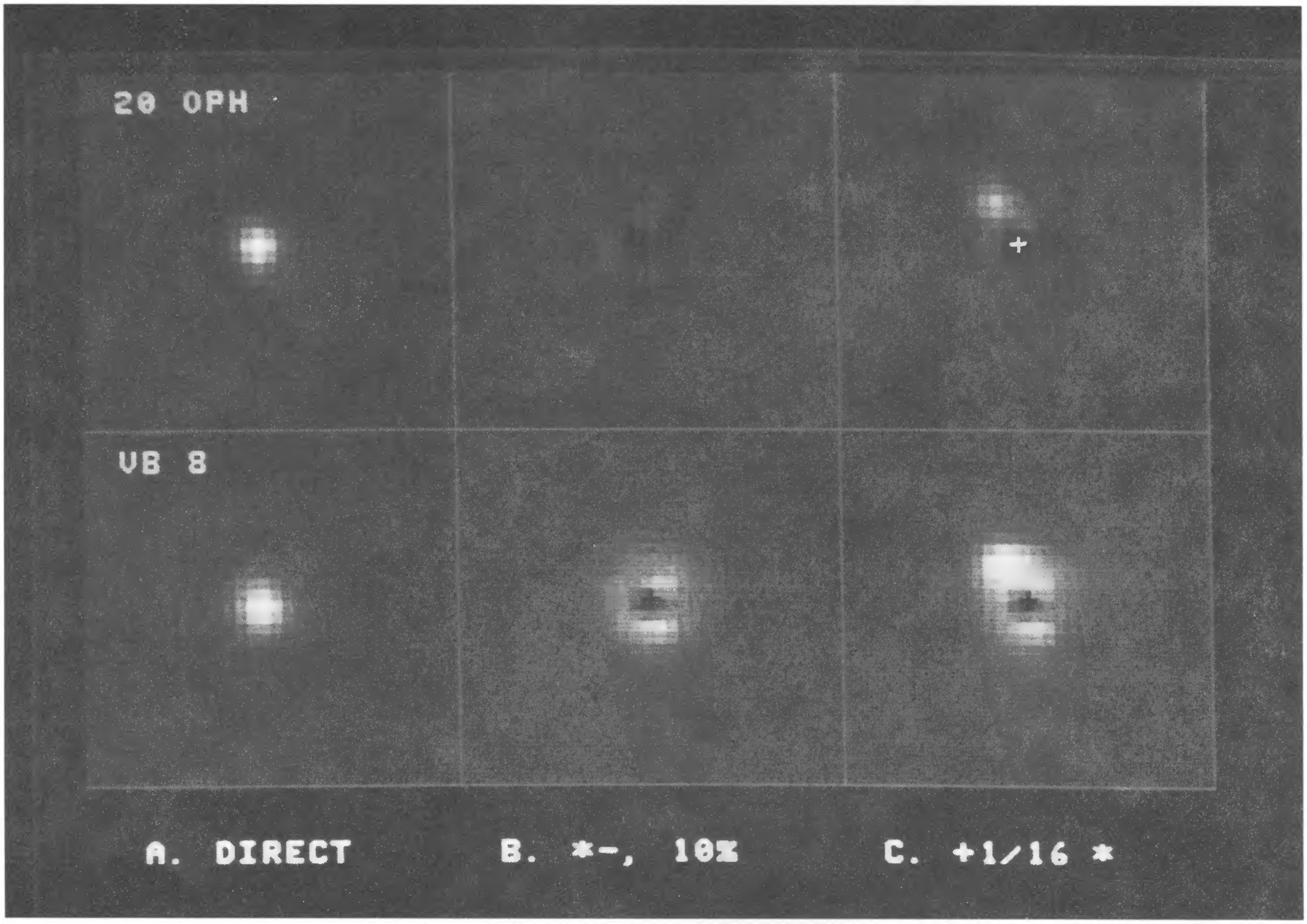

FIG. 2.—K (2.23 μm) images. Each frame is 7″ square with north up and east to the left. (*a*) First column: Composite K images of 20 Oph and VB 8. The 20 Oph image is the shifted-and-added sum of the last four 5 s exposures. The VB 8 image is a similar sum of four 5 s exposures. (*b*) Second column: Final sum of K images of VB 8 (*below*) and 20 Oph (*above*) with point-spread function subtracted (see text). The VB 8 image is composed of data from all 5 s exposures. The gray-scale maximum is scaled to 10% of the original source peak brightness. A cross marks the position of the original star. (*c*) Third column: Same as (*b*) with a false star added. The added star is the 20 Oph image in (*a*) scaled to 1/16 of the brightness of the original source (3.0 mag fainter) and positioned 1″ away at P.A. 27°. A cross marks the position of the original star. Scaling is the same as in (*b*). The saturation of pixels in the false star next to VB 8 is due to added signal from the underlying nebula.

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A more conservative approach, assuming that seeing created the nebula, involves using VB 8 itself to produce the false companion rather than 20 Oph. In this case a companion 1/16 as bright as the primary is still definitely visible but the companion 1/32 as bright is at the limit of detectability. In this worst case a companion more than 3.8 mag fainter than VB 8 at K would be undetectable.

A strong characteristic of a binary companion versus nebulosity is its asymmetry. Rotating the VB 8 image 180° in software about its centroid and subtracting it from the original tests for a companion independent of a calibrating source. Performing the analysis in this manner independently confirms the above results to comparable sensitivity.

For comparison, the 5 s images of 20 Oph were also shifted and subtracted from each other as described above for VB 8. We considered only independent pairs of 20 Oph images to eliminate redundant comparisons. The resulting image is shown in Figure 2*b*. The subtraction is quite good for the 20 Oph images and the remaining nebula is only 0.3% of the 20 Oph brightness. Also shown (Fig. 2*c*) is the subtracted nebula with a false star added, 1″ distant at P.A. = 27° and 3 mag dimmer than 20 Oph. The false star is unmistakable, demonstrating the ability of this experiment to detect such stellar companions.

According to the analysis of MPL, the proposed companion to VB 8 should be only 2 mag fainter than the primary at 3.75 μm if it has a blackbody spectrum because of its lower color temperature. Therefore the 3.75 μm images of VB 8 and 20 Oph offer a further sensitive test for a companion. Because of the high thermal background at these wavelengths, the signal-to-noise ratio in the 5 s exposures is considerably reduced from the 2.2 μm images. As summarized in Figure 1, the shifted-and-added L' images of VB 8 are slightly smaller than 20 Oph, but the variation in size between images is comparable to the difference in size between 20 Oph and VB 8. Therefore, the nebula seen at 2.2 μm is not evident at 3.75 μm.

Figures 3*a* and 3*b* (Plate L6) present all of the shifted-and-added images of VB 8 and 20 Oph at 3.75 μm. Subtraction of 20 Oph images from those of VB 8 once again provides a more sensitive test for a companion star. Rather than comparing individual 5 s exposures as before we chose to subtract composite images of the sources owing to the poorer signal-to-noise ratio at 3.75 μm. For each of the three composite VB 8 images (sums of six 5 s exposures) a comparison composite 20 Oph image (sum of four 5 s exposures) was chosen which most closely matched the fractional pixel position of the centroid in a 1″.9 diameter octagonal aperture. That image was then scaled to give zero total signal, shifted, and subtracted from the VB 8 image. The sum of the three VB 8 subtractions is shown in Figure 3*c*. The general structure is that of a bright core surrounded by a dark (negative) halo—consistent with the relative sharpness of the VB 8 images and the requirement of zero total signal. The bright residual peak is probably an artifact of the inability of this technique to remove the point-spread function close to the centers of the L' images. One arcsecond away from the position of the primary, the residual signal is quite weak and the search for a companion object is limited only by the intrinsic signal-to-noise ratio. Figure 3*d* shows a false companion of the sort suggested by MPL. The false star is a 20 Oph image, scaled to one-seventh the brightness of VB 8 and shifted 1″ from the center at position angle 27°. Referring to Figure 3*c*, clearly no star of this brightness 1″ from VB 8 is compatible with our direct images. A false star one-half as bright (1/14 of the VB 8 brightness) would also be clearly seen. We conclude that any companion to VB 8 at 1″ distance must be at least 3 mag dimmer than VB 8 at 3.75 μm.

III. DISCUSSION

As discussed above, the direct infrared images of VB 8 are incompatible with a pointlike companion of the type suggested by MPL. At both K and L' the limits to a companion 1″.0 away from VB 8 are 1 mag fainter than the reported values. The sensitivity of this experiment decreases for smaller separations and it would become difficult to detect the object described by MPL if it were less than 0″.6 from the primary. The minimum orbital period, assuming a maximum mass consistent with a brown dwarf companion and a circular orbit, is ~ 50 yr. This result in combination with limits to the astrometric perturbation of VB 8 by Harrington, Kallarakal, and Dahn (1983) preclude any significant change in the separation between the observations of MPL (1984 May) and this experiment (1985 July).

The direct images may be consistent with the speckle visibility data of MPL if a faint nebula surrounds VB 8. As noted above, when the point-spread function is removed from the VB 8 K images using 20 Oph images taken before and after VB 8, a nebula remains (see Fig. 2*b*). The nebula is ~ 2″ in diameter, slightly N–S elongated, and contains ~ 20% of the total flux. The present experiment is not adequate to unequivocably establish the reality of this nebula. Seeing or other variations in image quality at the 10%–20% level could produce a similar nebulosity artificially. The data on the image quality at K summarized in Figure 1 indicate quite stable images during the observing period. However, variations in seeing of ~ 10% cannot be ruled out. The speckle visibility data of MPL also imply extended structure in the VB 8 system. At K, ~ 10%–15% of the visibility is resolved at 0.5–1 arcsec^{-1} spatial frequency. This aspect of the visibility data could be explained by a faint nebula 1″–2″ in diameter with 10%–15% of the total flux surrounding VB 8, in rough agreement with the direct images. Taken together, the visibility and imaging data suggest extended emission surrounding VB 8. The image shown in Figure 2*b* is our best estimate of the shape and brightness of the nebula, but further observations will be required to firmly establish its existence.

A plausible mechanism for producing a nebula at K is scattering from dust grains in a circumstellar envelope. If the grains are much smaller than the wavelength, then the nondetection of the nebula at L' is expected. In this case, the grain scattering efficiency will be modulated by the Rayleigh factor, which varies as λ^{-4}, and falls by a factor of 8 from K to L'. The nondetection of a nebula at L', given the poor signal-to-noise ratio, is consistent with this hypothesis. However, one would then expect a quite bright nebula at H (1.65 μm),

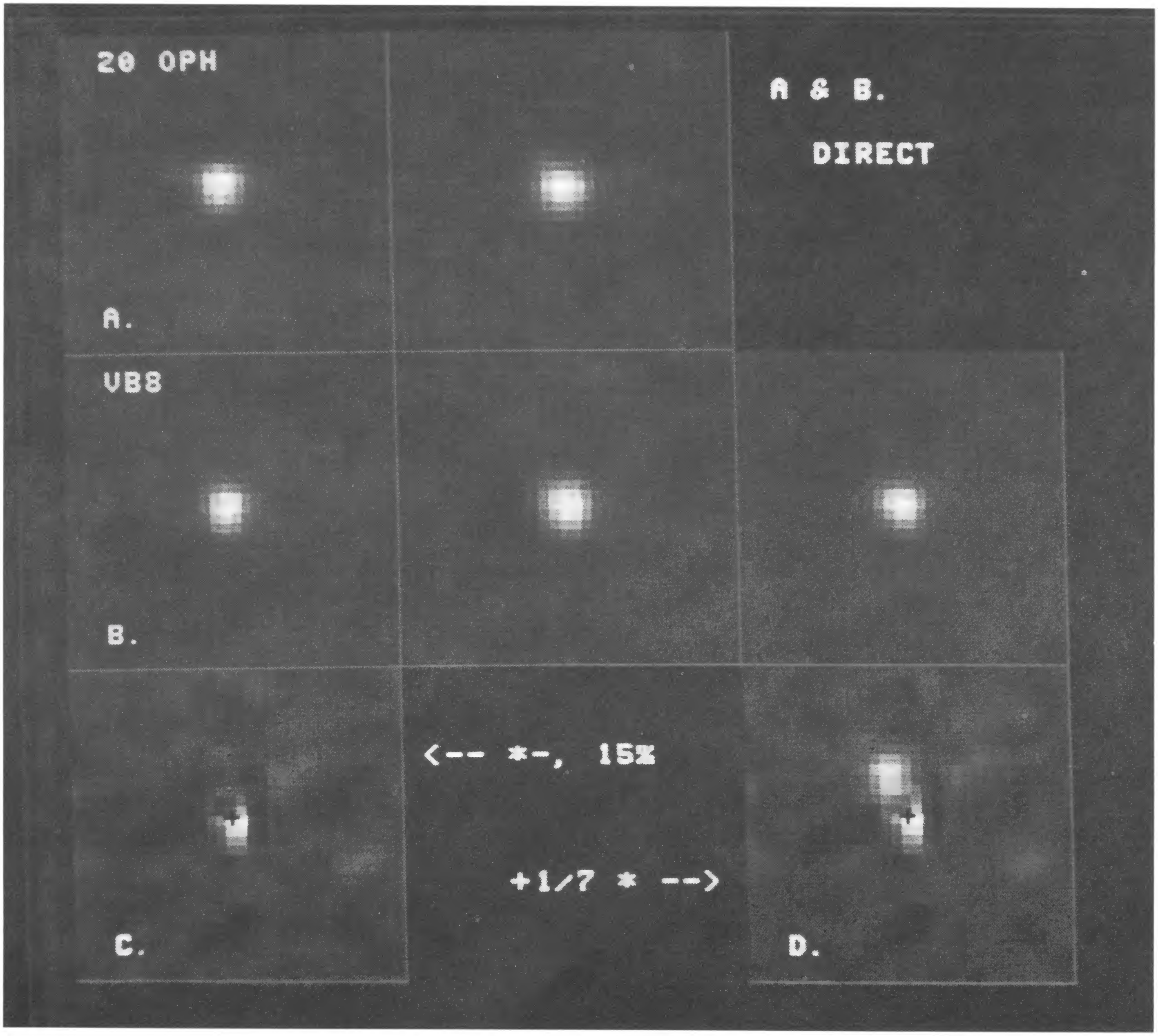

FIG. 3.—L' (3.75 μm) images. Each frame is 7″ square with north up and east to the left. (a) First row: The two shifted-and-added L' images of 20 Oph. Each is a composite of four 5 s images. (b) Second row: The three shifted-and-added L' images of VB 8. Each is a composite of six 5 s images. (c) Sum of the three VB 8 point-source–subtracted images (see text). The gray-scale maximum is scaled to 15% of the original VB 8 peak brightness. (d) Same as (c) with a false star added. The added star is a 20 Oph image scaled to one-seventh of the original VB 8 brightness (2.1 mag fainter) and positioned 1″ away at P.A. 27°. A cross marks the position of the original star. Scaling is the same as in (c).

SKRUTSKIE, FORREST, AND SHURE (*see* page L57) whereas MPL find the extended structure weaker relative to the star. Thus this model requires peculiar grain properties: efficient at scattering 2.2 μm radiation but not at 1.65 μm or 3.75 μm. Although such scattering properties may be awkward to explain, McCarthy (1986) reports asymmetric extended emission peaking in the near-infrared surrounding another main-sequence M star, Lalande 21185. Here the peak emission is in the H (1.65 μm) photometric band (D. W. McCarthy, personal communication). VB 8 may be a member of this class of object with the star centered on the nebula. If so, this phenomenon may represent a new class of nebulae with unusual scattering properties associated with main-sequence M dwarf stars.

A surprising aspect of this nebula is that it contributes 10%–20% of the K band flux. If this is scattered light, then the nebula must subtend at least 10%–20% of the solid angle surrounding the star. This is a very substantial nebula. In comparison, the circumstellar nebulae found around earlier type main-sequence stars by *IRAS*, such as α Lyrae (Aumann *et al.* 1984) and β Pictoris Austrinus (Smith and Terrile 1985) absorb only $\sim 10^{-4}$ of the total starlight and scatter a similar small fraction of the starlight in the visible. On the other hand, potential protoplanetary nebulae around protostars such as HL Tau (Beckwith *et al.* 1984; Grasdalen *et al.* 1984) scatter a substantial portion of the stellar flux, similar to VB 8.

VB 8 does not appear in the *IRAS* point source survey. The equilibrium temperature of dust 4 AU (0\".7) from VB 8 is between 25 and 70 K depending on the particle size and emissivity, and the peak emission is in the far-infrared. If 10% of the flux from VB 8 is absorbed and reradiated the 60 and 100 μm flux densities would be $\sim$ 0.5–1 Jy. The detection limit for the *IRAS* point source survey is 0.4 Jy at 60 μm and 1 Jy at 100 μm, equivalent to the expected flux. Averaging all of the available *IRAS* scans of this field using a point-source filter reduces the 3 σ flux densities to 100 mJy at 60 μm and 300 mJy at 100 μm. VB 8 was not detected (3 σ) in these data at either wavelength. This result marginally rules out the hypothesis that VB 8 is surrounded by a dusty nebula. However, the estimates of the expected flux density above are quite uncertain. Near-infrared polarization studies or more sensitive far-infrared observations from the Kuiper Airborne Observatory, or eventually from SIRTF or ISO, could determine if the nebula is real or an artifact of the variations in seeing.

IV. CONCLUSIONS

Direct infrared imaging of VB 8 in the K and L' photometric bands shows no evidence of a brown dwarf companion 1\" away from VB 8. A faint nebulosity surrounding the star may explain the visibility curves of MPL. A similar nebula observed near another late-type main-sequence star supports this conclusion. Rather than demonstrating the existence of brown dwarfs, the visibilities for VB 8 may be further evidence of a new astronomical phenomenon of infrared nebulosities surrounding late M dwarfs. VB 8B was the best candidate yet for a truly substellar object. Its disappearance would push the subject of brown dwarfs back toward the realm of theoretical speculation. As evidence grows that the faint end of the main-sequence represents a true cutoff in the luminosity function, the distinction between stars and planets becomes ever sharper, and the role of brown dwarfs all the more fascinating.

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W. J. Forrest and M. A. Shure: Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627

M. F. Skrutskie: Astronomy Department, Space Sciences Building, Cornell University, Ithaca, NY 14853