A SEARCH FOR CLOSE BINARIES IN THE $\rho$ OPHUCHI STAR-FORMING REGION

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ABSTRACT

We have carried out a new, near-infrared speckle imaging survey of 19 members of the young stellar population in the nearby ($d = 140$ pc) $\rho$ Oph cloud core. Results for four binary and one newly discovered triple system are reported. Data for all known multiple systems among the pre–main-sequence population of $\rho$ Oph are tabulated. We define a restricted binary fraction, $F_{br}$, and a restricted companion fraction, $F_{cr}$, as counting only those systems most detectable in the present and previous high-resolution near-infrared imaging surveys having separations between 0\"1 and \~{}1\"6 and $K$-band magnitude differences $\Delta K < 3$. Analysis of all the available multiplicity data results in updated values of $F_{br} = 24\% \pm 11\%$ and $F_{cr} = 24\% \pm 11\%$ for the Ophiuchus pre–main-sequence population. These values are consistent with the values in the Taurus star-forming region, and $F_{cr}$ is in excess by a factor of 2 relative to the main sequence at the 1 $\sigma$ level.

Subject headings: binaries: close — infrared: stars — stars: pre–main-sequence — techniques: high angular resolution

1. INTRODUCTION

The formation of binary and multiple stars is a natural consequence of present-day star formation, yet many basic questions regarding this process remain unanswered. What is the frequency of multiple systems in the nearest star-forming regions to Earth? What is the distribution of source separations among pre–main-sequence binaries? Does this distribution evolve with time as the stars join the main-sequence field population? Does the binary separation distribution vary with disk parameters, and if so, how? Do close binaries affect the appearance of each individual disk, and if so, how?

It has been suggested that the binary frequency among T Tau stars in Taurus and Ophiuchus is higher than among the nearby solar-like stars in a restricted separation range (Ghez, Neugebauer, & Matthews 1993; Leinert et al. 1993). This separation range is 0\"1–1\"8, corresponding to projected linear separations of 14–250 AU at an assumed 140 pc distance to the Taurus and Ophiuchus star formation regions. Subsequent investigations of this claim have found conflicting, or at least ambiguous, results for different star-forming regions (e.g., Prosser et al. 1994; Simon et al. 1995; Beck, Simon, & Close 2003). In Ophiuchus in particular, there have been too few known multiple systems, with too few systems searched with comparable techniques, to have enough statistics for comparison with the main-sequence population and with other star-forming regions.

One problem, until recently, had simply been that too few actual cloud members were known in $\rho$ Oph (e.g., Wilking, Lada, & Young 1989). This is due to the high overall extinction toward the $\rho$ Oph cloud core, in contrast to the much lower extinction toward members of the young stellar population in Taurus. The advent of recent satellite data identifying young stellar objects (YSOs) in $\rho$ Oph from the X-ray (Casanova et al. 1995; Grosso et al. 2000; Imanishi, Koyama, & Tsuboi 2001) and the mid-infrared (Bontemps et al. 2001) wavelength regions has significantly increased the known number of cloud members. Large-area, magnitude-limited, near-infrared surveys of $\rho$ Oph have recently become available (2MASS; Barsony et al. 1997). The vast majority (~95%) of the near-infrared sources are background objects. However, positional cross-correlation of the near-infrared sources with lists of known cloud members, arrived at through observations at X-ray, mid-infrared, or optical wavelengths, allows the identification of suitable targets that meet the joint criteria of cloud membership and being bright enough at the $K$ band (2.2 $\mu$m) for speckle imaging.

Once cloud members have been identified, a survey for multiplicity should ideally be undertaken such that all targets are searched using uniform criteria. The lack of consistency of previous surveys has made it difficult to draw firm conclusions regarding the binary fraction in $\rho$ Oph. Previous multiplicity surveys in $\rho$ Oph have used a variety of search techniques, including spectroscopy and imaging, at different wavelengths (either near-infrared or optical), with different sensitivities, valid over different separation ranges.

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2 2MASS Second Incremental Release Point Source Catalog available at http://irsa.ipac.caltech.edu.
One would ideally use a single technique, with the same sensitivity for all targets searched, obviating the need for various corrections due to lack of uniform data (e.g., Duchene 1999).

The largest number of binary identifications among pre-main-sequence members of the Tau-Aur dark clouds were found by high-resolution near-infrared imaging techniques (Ghez et al. 1993; Leinert et al. 1993; Simon et al. 1995). In practice, these techniques require relatively bright targets ($K < 8.5$ on a 5 m aperture telescope for speckle imaging).

We have undertaken a new near-infrared speckle imaging survey of bona fide $\rho$ Oph cloud members at the Hale 5 m telescope. Since the Chandra, ROSAT, and ISOCAM surveys covered rather limited areas, of order $35' \times 35'$, containing rather few bright $K$-band targets that had not previously been searched, we supplemented our target list with bright $K$-band sources that are optically identified cloud members, either from large-area ground-based H$\alpha$ surveys (Struve & Rudjeboring 1949; Dolidze & Arkelyan 1959; Wilking, Schwartz, & Blackwell 1987) or via optical follow-up imaging of Einstein-identified cloud members (Bouvier & Appenzeller 1992).

We report our target list, observing procedures, and data reduction methods in § 2. The results of this speckle survey are presented in § 3. In § 4 we have collected published data on 49 separate multiple systems in Table 3, and the data on all systems found to be singles via high-resolution near-infrared techniques in Table 4, in order to be able to draw valid, statistically significant conclusions about the binary separation distribution and the binary fraction in $\rho$ Oph. We summarize our findings in § 5.

2. OBSERVATIONS AND DATA REDUCTION

Speckle observations of the 19 pre-main-sequence stars in the sample were made in the near-infrared $K$ band on 2002 May 24–25 at the 5 m Hale telescope on Palomar Mountain. An external optical system (reimager) magnified the telescope platescale to produce a pixel size of $0^\prime 034 \pm 0^\prime 001$, sufficient to Nyquist sample the $0^\prime 1$ diffraction limit of the telescope (Weinberger 1998). The detector was D-78, a camera at the Cassegrain focus that was equipped with a $256 \times 256$ pixel InSb array, of which we used the central $64 \times 64$ pixels, giving a field of view of $27^\prime$. The orientation accuracy of the detector is $0^\prime 5$. The seeing was typically $0^\prime 75$ FWHM. The presence of thin cirrus prevented us from obtaining absolute photometry.

The observing procedure was typical for speckle interferometry, with the exception that the chopping secondary was used to switch rapidly between the position of the science target and the blank sky $30^\prime$ away. Briefly, the data consisted of a series of 560 frames with 0.1 s exposure times—fast enough to “freeze” the atmospheric seeing and preserve diffraction-limited image information. Sky exposures were interleaved with the exposures on the science target. In total, each series contained 490 frames on the target and 60 on the sky position, with the remaining 10 being rejected while the secondary’s position was changing. At least eight such series were obtained on each science target, along with a similar number on an unresolved reference star. The reference star series were interleaved with the target star series to reduce sensitivity to seeing and focus changes. A log of the observations is given in Table 1.

Reduction of the data consisted of the usual flat-fielding and sky subtraction of the raw frames, followed by computation of the Fourier power spectrum and bispectrum (Lohman, Wiegelt, & Wirnitzer 1983) averaged for the on-source frames in each series. The power spectrum of the calibrated sky frames in the series was subtracted from that of the on-source frames, and the Fourier phase for the series was reconstructed from the bispectrum using the recursive technique. The results for the science target series were calibrated pairwise with the results for the reference star series to remove the distortions due to the atmosphere and the telescope. The calibration consisted of simple division of the sky-subtracted Fourier power spectra and subtraction of the reconstructed Fourier phases. The calibrated Fourier transform data were then averaged over the series for each science target. Finally, the calibrated Fourier data were apodized to approximately diffraction-limited resolution and Fourier transformed to recover a calibrated high-resolution image.

Basic parameters (the separation, position angle, and brightness relative to the primary) for the companions in the detected binary and triple systems were derived by fitting models to the calibrated Fourier data. Parameter uncertainties were estimated by fitting simulated data representing binaries with parameters close to the observed values. The simulated data were created by calibrating reference star files against each other to produce Fourier power spectra and phases for point sources. Their noise should be very similar to that for the calibrated science target data. The modulations corresponding to double stars were then impressed onto the point-source power spectra by multiplying them by the power spectra of model doubles, and onto the point-source phases by adding the phases of the model doubles. In total, 23 independent simulated Fourier transforms were constructed for each real double detected in our survey. The results of fitting these simulated data could then be compared directly to the true model parameter values.

| Target | Night (2002 May) | Series | R.A. (J2000.0) | Decl. (J2000.0) |
|--------|-----------------|--------|----------------|----------------|
| V852 Oph | ................. | 24     | 8              | 16:25.22:16    | −24:30:13.7 |
| ROXa 2 | ................. | 24     | 8              | 16:25.24:37    | −23:55:09.9 |
| IRS 2 | ................. | 24     | 8              | 16:25.36:75    | −24:15:42.1 |
| ROXa 4/IRS 10 | ........... | 24     | 8              | 16:25.50:53    | −24:39:14.3 |
| ROXa 10A/DoAr 24 | ....... | 24     | 8              | 16:26.17:09    | −24:20:14  |
| ROXa 9A | ................. | 24     | 8              | 16:26.23:99    | −25:47:16.1 |
| ROXa 9B | ................. | 24     | 8              | 16:26.30:72    | −25:43:39.8 |
| ROXa 9C | ................. | 24     | 8              | 16:26.37:95    | −25:45:12.8 |
| GY 292 | ................. | 24     | 10             | 16:27.33:11    | −24:41:15.1 |
| ROXa 35A | ................. | 24     | 8              | 16:27.38:31    | −23:57:32.9 |
| WSB 52/GY 314 | ......... | 24     | 8              | 16:27.39:43    | −23:45:15.5 |
| ROXa 29/SR 9 | ........... | 24     | 8              | 16:27.40:28    | −23:42:04.3 |
| ROXa 40 | ................. | 24     | 8              | 16:30.51:51    | −23:11:40.0 |
| WSB 69A | ................. | 25     | 10             | 16:31.04:37    | −24:04:33.3 |
| WSB 69B | ................. | 25     | 8              | 16:31.05:17    | −24:04:40.3 |
| ROXa 42C | ................. | 24     | 8              | 16:31.15:75    | −24:34:02.2 |
| ROXa 44 | ................. | 24     | 8              | 16:31.33:45    | −24:37:31.1 |
| IRAS 16289–2457 | ........ | 24     | 8              | 16:31.54:74    | −25:03:33.8 |
| ROXa 47A | ................. | 24     | 8              | 16:32.11:81    | −24:40:21.3 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
The values we quote are the rms scatter among the fits to the simulated data sets. We found that the separation error was independent of the separation and close to 0.03 for all doubles, while the position angle error ranged from ~0.2° for separation 0″7 to 2″6 for the marginally resolved double with separation 0″04. The brightness ratio errors (with the ratio defined as the brightness of the fainter star divided by that of the brighter one) are ~0.03 for the fully resolved doubles and 0.15 for the marginally resolved double. These error estimates do not include the uncertainties in the image scale and orientation of the detector. Further, there is a 180° ambiguity in the position angle of the marginally resolved double in the ROXs 47A hierarchical triple system.

3. RESULTS

Of the 19 target objects for which we acquired near-infrared speckle data, five were resolved into multiple systems. Figures 1, 2, 3, 4, and 5 show images related to each multiple system, with three frames plotted for each of the five panels. The leftmost frames represent the calibrated power spectra, and the middle frames represent the Fourier phases, both plotted over spatial scales in the range 1″1 at the circles’ centers, corresponding to approximately half the field-of-view of the portion of the detector that was used, to the diffraction limit of 0″1, at the circles’ outer peripheries. The rightmost frame in each panel shows the final reconstructed image for each target object. Only one system, the ROXs 47A triple system, is a newly reported multiple (see Table 2).

In Table 2 we present the parameters of the systems shown in Figures 1–5. Column (1) lists the target’s name, column (2), the component separations in arcseconds, column (3), the position angle, east of north, relative to the brighter object at K, and column (4) lists the flux ratio between the components at K. For reference, we also tabulate previously reported binary parameters, when available, in column (5) of Table 2. Comparison with the previously published data for four systems in Table 2 shows no discernible change in separations and position angles for the ROXs 2, IRS 2, and ROXs 29 binary systems. There is quite a large change in the ROXs 42C hierarchical triple system, however. Between 1990 July 8 and 2002 May 24, the projected source separation increased by 0″12 (corresponding to 17 AU at a distance of 140 pc), while the position angle has advanced by 18°.

4. DISCUSSION

4.1. Distribution of Binary Separations

The distribution of binary separations is of interest to identify any possible evolution of this quantity with age when compared with main-sequence stars, as well as to
compare this distribution among different star-forming environments. The original motivation for examining the pre–main-sequence distribution of binary separations was to test the hypothesis that the apparent excess of pre–main-sequence multiple systems observed in Taurus and Sco-Oph, reflects a distribution in the pre–main-sequence phase that is more strongly peaked in the range of separations to which the surveys are most sensitive \((0.1 < a < 1.0)\), rather than a true excess of multiples. In this scenario, there would be an evolution of the shape of the distribution of binary separations with time, with the distribution becoming flatter by the time the stars reach the main sequence (Ghez et al. 1993).

In order to have a statistically significant sample for the determination of the distribution of binary separations among the young stellar population in \(\rho\) Oph, we have compiled a list of all the multiple sources so far identified in the literature, in addition to the multiple systems identified in the study reported here. This compilation is presented in Table 3. Column (1) of Table 3 lists each young stellar object’s name, with some common alternate names for the object listed in column (8). Note that the designation ROX refers to “Rho Oph X-ray” source as detected by the Einstein Observatory (Montmerle et al. 1983), whereas ROXs refers to an optically detected object that falls within the rather large Einstein X-ray source error circle. This distinction is important, because in some cases more than one optical counterpart is associated with a single Einstein source (Bouvier & Appenzeller 1992).

Since, unfortunately, it is not unusual for a single source to have a dozen or more names in \(\rho\) Oph, for ease of identification and for reference, coordinates are necessary. We have therefore included J2000.0 coordinates, good to \(\pm 0.2\), from the Two Micron All Sky Survey (2MASS) database (unless otherwise indicated) for each object in columns (2) and (3) of Table 3. Column (4) of Table 3 indicates the type of multiplicity: whether the system is binary, spectroscopic binary, triple, or quadruple. Columns (5) and (6) list the component separations in arcseconds, and the position angle between the components, measured east of north, from the brighter source at \(K\), respectively. Column (7) lists the reference from which the multiplicity data were gleaned, with the first listed reference being the one from which the data in columns (5) and (6) are taken. Finally, in addition to alternate common names for the given target, comments are also included in column (8) of Table 3.

Among the 49 independent multiple systems listed in Table 3, there are 62 separations, which are plotted in the histogram of Figure 6. This represents an eightfold increase in the number of separations available for study of the pre–main-sequence population in \(\rho\) Oph since the last such published histogram (see Simon et al. 1995). The data in Figure 6 are binned in intervals of \(P\), as in previous authors’ works (Duquennoy & Mayor 1991; Simon et al. 1995). The
overplotted curve is the separation distribution based on the period distribution for main-sequence solar-type field stars (Duquennoy & Mayor 1991). The conversion from a period to a separation distribution uses the same assumptions as previous authors, i.e., two 0.5 \( M_\odot \) stars in a circular orbit at a distance of 140 pc (Simon et al. 1995). The vertical scale of the main-sequence distribution is chosen to correspond to a distance of 140 pc (Simon et al. 1995). The vertical scale of the histogram (62).

We note that this sample is reasonably complete over the 0.1 \( a \leq 2^\prime \) projected separation interval but may be seriously incomplete at the closest separations (where spectroscopic searches are necessary) and at the larger (>10\( \prime \)) separations, where few systematic searches have been undertaken and where contamination by background objects becomes an issue.

There are not yet enough individual components of the multiple systems listed in Table 3 that have classifications available as to whether they are WTTS (weak-lined T Tau stars), lacking accretion disks, or CTTS (classical T Tau stars), with accretion disks, to draw meaningful conclusions from the comparison of the WTTS versus CTTS binary separation distributions. Such a comparison would be interesting for the study of the effects of binarity on disk evolution. In this context, we note that a recent *Hubble Space Telescope* spectroscopic study of a sample of 20 close (\( \leq 1^\prime \)) binaries in Taurus found that four (20\%) turn out to be in mixed CTTS/WTTS pairs (Hartigan & Kenyon 2003). Furthermore, there is a strong selection effect against finding spectroscopic binaries among the CTTS, i.e., against finding CTTS at the closest separations, since the veiling and emission lines characteristic of CTTS can easily overwhelm the photospheric absorption lines that are generally used to find spectroscopic binaries. With these caveats, however, hopefully the individual components of the multiple systems in Table 3 will be characterized in the near future, and the samples will become large enough to allow just such a comparison.

### 4.2. Binarity and Multiplicity Fraction of the \( \rho \) Oph Pre–Main-Sequence Population

An accurate determination of the multiplicity fraction of the young embedded population in \( \rho \) Oph presumes, first of all, that our search list is restricted to bona fide association members (excluding foreground or background objects). In practice, this means that each target object has at least one indicator of young stellar object status, such as bright X-ray emission, broad H\( \alpha \) equivalent width, photospheric Li absorption, associated nebulosity, high percentage optical absorption, photospheric Li absorption, associated nebulosity, high percentage optical

### Table 2

**Characteristics of Multiple Systems Detected in This Survey**

| System     | Separation (arcsec) | P.A. (deg) | Flux Ratio\( b \) | Reference |
|------------|---------------------|------------|------------------|-----------|
| ROXs 2     | 0.42 ± 0.03         | 347.1 ± 0.2| 1.75 ± 0.1       | 1         |
| IRS 2      | 0.41 ± 0.03         | 349 ± 1    | 2.58 ± 0.3       | 2         |
| ROXs 29/SR 9/Elias 34 | 0.42 ± 0.03 | 77.6 ± 0.4 | 8.0 ± 2.5       | 1         |
| ROXs 2     | 0.44 ± 0.03         | 79 ± 4     | 7.58 ± 0.4 at H\( \alpha \) band | 2 |
| ROXs 42\( c \) | 0.63 ± 0.03 | 353.3 ± 0.05 | 12 ± 5     | 1         |
| ROXs 47A   | 0.59 ± 0.01         | 350 ± 1    | 11 ± 2.13 ± 2   | 3         |
| ROXs 47A\( c \) | 0.28 ± 0.03 | 152.9 ± 0.5 | 4.4 ± 0.7     | 1         |
| ROXs 47A\( c \) | 0.157 ± 0.003 | 135 ± 3     | 4.0 ± 0.34     | 3         |
| ROXs 47A\( c \) | 0.04 ± 0.03 | 107 ± 20    | 1.1 ± 0.7      | 1         |

\( a \) All flux ratios are at the \( K \) band, except where otherwise noted.

\( b \) This is a triple system, with one component consisting of a spectroscopic binary; see Mathieu et al. 1989.

\( c \) Due to the extreme proximity of the components, there remains a 180\(^\circ\) ambiguity in the position angle of the close binary in this hierarchical triple system.

References.—(1) This work; (2) Costa et al. 2000; (3) Ghez et al. 1993.
| Name         | (J2000.0) | (J2000.0) | System Type | Separation (arcsec) | P.A. Degree | Reference | Other Aliases |
|--------------|-----------|-----------|-------------|---------------------|-------------|-----------|--------------|
| 155203-2338  | 15 54 59.87 | -23 47 18.2 | B           | 0.80               | 229         | 1         |              |
| WSB 3        | 16 18 49.81 | -26 32 53.3 | B           | 0.62               | 162         | 2         |              |
| WSB 4        | 16 18 49.66 | -26 10 06.2 | B           | 0.84               | 128.5       | 3, 2      | IRCd(2)      |
| WSB 11       | 16 21 57.3  | -22 38 16   | B           | 0.50               | N.A.        | 2         |              |
| WSB 18       | 16 24 59.79 | -24 56 00.3 | T(Q?)       | 1.08               | 80.4        | 3, 2      | Faint 2MASS source at 10° separation |
| WSB 18A      | 16 25 02.13 | -24 59 31.8 | B           | 0.10               | 339.55      | 3, 2      | Primary is double |
| WSB 19       | 16 25 10.5  | -21 19 14   | B           | 1.00               | 23          | 4, 2      |              |
| ROX 1        | 16 25 19.28 | -24 26 52.1 | B           | 0.236              | 156         | 1, 5      | SR 2, SAO 184375, Elias 6, GSS 5, 162218–2420 |
| HD 147889    | 16 25 24.32 | -24 27 56.6 | B           | 4.09 \times 10^{-4} | N.A.       | 6         |              |
| ROXs 2       | 16 25 24.37 | -23 55 09.9 | B           | 0.41               | 349         | 7, 8      |              |
| IRS 2        | 16 25 36.75 | -24 15 42.1 | B           | 0.44±0.03          | 79±4        | 7, 8      |              |
| ROXs 5       | 16 25 55.86 | -23 55 10.1 | B           | 0.13               | 130         | 9         | DoAr 23      |
| WSB 26       | 16 26 18.40 | -25 20 55.6 | B           | 1.15               | 23.8        | 3, 2      |              |
| WSB 28       | 16 26 18.40 | -25 20 55.6 | B           | 1.15               | 23.8        | 3, 2      |              |
| IRS 44       | 16 27 28.17 | -24 27 43.5 | B           | 0.25±0.03          | 26.6±0.7    | 6         |              |
| ROXs 20B     | 16 27 19.52 | -24 41 40.4 | B           | 0.30±0.03          | 85          | 10, 7     | ROXc 21, IRS 40, GY 250 |
| IRS 42       | 16 27 21.48 | -24 41 43.0 | B           | 26.8               | 85.8        | 10, 7     | 10, 7 found IRS 42 single |
| ROXs 20+ROXs 20B |           |            | B           | 10.0               | 122         | 12, 10    | YLW 1 5A; CRBR 85 is 34° away |
| ROXs 20A     | 16 27 14.51 | -24 31 33.4 | B           | 239                | 14          |          |              |
| ROXs 20B     | 16 27 15.15 | -24 31 88.8 | B           | 24.7               | 14          |          |              |
| WLS 2        | 16 27 15.69 | -24 38 43.4 | B           | 3.17               | 270         | 16        | East-west separation |
| WLS 20       | 16 27 15.72 | -24 38 45.6 | B           | 2.26               | 173         | 16        | Southwest separation |
| WLS 20e      | 16 27 15.89 | -24 38 43.4 | B           | 3.66               | 232         | 16        | Southeast separation |
| SR 12        | 16 27 16.59 | -24 41 40.4 | B           | 0.30±0.03          | 85          | 10, 7     | ROXc 21, IRS 40, GY 250 |
| IRS 42       | 16 27 21.48 | -24 41 43.0 | B           | 26.8               | 85.8        | 10, 7     | 10, 7 found IRS 42 single |
| ROXs 20A     | 16 27 14.51 | -24 31 33.4 | B           | 239                | 14          |          |              |
| IRS 43       | 16 27 26.94 | -24 40 50.0 | B           | 12.5               | 13, 10, 7   | 12, 10    | YLW 1 5A; CRBR 85 is 34° away |
| IRS 44+GYS 26 | 16 27 26.94 | -24 40 50.0 | B           | 12.5               | 13, 10, 7   | 12, 10    | YLW 1 5A; CRBR 85 is 34° away |
| IRS 44       | 16 27 26.94 | -24 39 23.0 | B           | 23.21              | 13          |          |              |
| IRS 44       | 16 27 28.01 | -24 39 33.6 | B           | 0.27               | 81          | 12, 13, 7, 10 | YLW 16A |
| WR 13        | 16 27 27.40 | -24 31 16.6 | B           | 0.46               | 356         | 7         | VSSG 25; Elias 31 |
| WSSG 17      | 16 27 30.17 | -24 27 43.5 | B           | 0.25±0.03          | 26.6±0.7    | 6         | Elias 33; IRS 47/GY 279 |
| DoAr 32+DoAr 33 | 16 27 38.31 | -23 57 32.9 | B           | 10.06              | 332.1       | 9         | WSB 51, ROXs 30B (Primary) |
| DoAr 32      | 16 27 38.31 | -23 57 32.9 | B           | 10.06              | 332.1       | 9         | WSB 51, ROXs 30B (Primary) |
| DoAr 33      | 16 27 39.00 | -23 58 19.0 | B           | 5.9                | 350         | 4, 1, 8   | ROXs 29, Elias 34, GY 319 |
| VSSG 14      | 16 27 49.86 | -24 25 40.5 | B           | 0.10               | 89          | 10        | Elias 36; GY 372 in 18°/34 away |
| ROXs 31      | 16 27 52.07 | -24 40 50.4 | B           | 0.39               | 71.6        | 9, 10, 18, 7 | IRS 55/GY 380/HBC 642 |
polishing, infrared excess, and/or a distance determination placing it at the cloud’s distance of \( \sim 140 \pm 20 \) pc.

A second requirement for an accurate determination of the multiplicity is knowledge of the number of systems that have been searched for multiplicity by various authors but were found to be single. We want the search sensitivities to be as uniform as possible. Therefore, we restrict this analysis to objects searched for multiplicity with near-infrared techniques that are generally sensitive to source separations \( 0.1 < r < 1 \) and \( \Delta K < 3 \) mag. These joint criteria have the added benefit of effectively excluding background objects that may be chance projections toward the same line of sight as the target objects.

In Table 4, therefore, we list all of the target objects searched for multiplicity by searches that would have been sensitive to detecting binaries with source separations in the range \( 0.1 < r < 1 \) and with component magnitude differences \( \Delta K < 3 \) mag. These surveys used various techniques, such as speckle observations, as reported here and elsewhere (Ghez et al. 1993; Ageorges et al. 1997), lunar occultation measurements (Simon et al. 1995), and shift-and-add imaging data (Costa et al. 2000; Haisch et al. 2002). In Table 4, each target object’s name is listed in column (1); its J2000.0 coordinates, from the 2MASS Second Incremental Release Point Source Catalog, are listed in columns (2) and (3), and the authors who have searched each target for multiplicity Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

- B = binary; SpB = spectroscopic binary; T = triple; Q = quadruple.
- P.A. s are east of north, measured from the primary at \( K \).
- Separations and P.A. s listed are from the first reference.
- IRC = Infrared Companion system.
- Coordinates for WSB 11, WSB 20, and WSB 35 are from the SIMBAD database; these sources fell outside the 2MASS survey’s areal coverage.
- See text for discussion of IRS 43, IRS 44, and IRS 51.

References.—(1) Ghez et al. 1993; (2) Reipurth & Zinnecker 1993; (3) Koresko 2002; (4) Geoffray & Monin 2001; (5) Aitken 1932; (6) Haffner & Meyer 1995; (7) Costa et al. 2000; (8) this work; (9) Ageorges et al. 1997; (10) Simon et al. 1995; (11) Chelli et al. 1988; (12) Haisch et al. 2002; (13) Terebey et al. 2001; (14) Barsony et al. 1989; (15) Bouvier & Appenzeller 1992; (16) Ressler & Barsony 2001; (17) Barsony et al. 1997; (18) Simon et al. 1987; (19) Mathieu et al. 1989.

### TABLE 3—Continued

| Name         | \( \alpha (J2000.0) \) | \( \delta (J2000.0) \) | System Type | Separation (arcsec) | P.A. Degree | Reference | Other Aliases |
|--------------|------------------------|------------------------|-------------|---------------------|-------------|-----------|--------------|
| SR 20        | -24 22 45.0            | B                      | 0.071       | 225                | 1, 10       | ROX 33, WSB 61, HBC 643; DoAr 38 |
| V853 Oph     | -24 28 18.9            | T                      | 0.43        | 97                 | 10, 1, 7, 4 | SR 13, WSB 62 |
| V853 Oph A   |                        |                        | 0.013       | 96                 | 10          | Primary resolved |
| Haro 1-14+   | B                      |                        | 12.9        | 122                | 2           | Primary |
| Haro 1-14    |                        |                        | -24 04 33.3 |                    |             | WSB 69; secondary |
| ROX 42B      | -24 32 43.7            | B                      | 0.056       | 89                 | 10          | SpB 19 |
| ROX 42C      | -24 34 02.2            | T                      | 0.157       | 135                | 1, 8 = SpB 19 |
| ROX 43       |                        |                        | 0.00195     |                   |             | SpB 19 |
| ROX 43 A     | -24 30 05.0            |                        | 0.0028      | N.A.               | 19          | SpB 19 |
| ROX 43 B     | -24 30 00.7            |                        | 0.016       | 89                 | 10          | SpB 19 |
| WSB 71       |                        |                        | 3.56        | 35.0               | 3, 10       | Faint 2MASS source 77330 from WSB 71A |
| WSB 71 A     | -24 24 39.9            |                        | -24 24 39.9 |                    |             |          |
| WSB 71 B     | -24 24 37.0            |                        | -24 24 37.0 |                    |             |          |
| L1689 IRS S  | -24 56 15.7            | B                      | 2.92        | 240.3              | 12          | L1689 SNO 2 |
| ROX 45 E+    | -24 56 15.7            | B                      | 15.0        | 75                 | 15          |          |
| ROX 45 E     | -24 50 29             |                        | -25 30 29   |                    |             | DoAr 49 |
| ROX 45 F     | -25 30 25             |                        | -25 30 25   |                    |             | DoAr 50 |
| ROX 47 A     | -24 40 21.3            | T                      | 0.813       | 80.5               | 8           |          |
| ROX 47 Ab    | -24 40 21.3            | T                      | 0.046       | 107.9 or 287.9     | 8           |          |
| HD 150193    | -24 53 43.5            | B(T?)                  | 1.09        | 221.7              | 3           | Elias 49 (HAeBe); 2MASS source at 133°1 |

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**Fig. 6.**—Distribution of the separations of the pairs in the binary and multiple systems of Table 3. The overplotted curve corresponds to the distribution of separations in solar-type main-sequence stars as measured by Duquennoy & Mayor (1991) and is scaled to correspond to the number of pre-main-sequence systems plotted. The separations for the main-sequence stars are computed according to the same assumptions used by previous workers: a distance of 140 pc, stellar component masses of 0.5 \( M_\odot \), and circular orbits.
TABLE 4

| Object Name | R.A. (J2000.0) | Decl. (J2000.0) | Reference |
|-------------|----------------|----------------|-----------|
| WSB 16/DoAr 15*........................| 16 23 34.7 | -23 40 29.0 | 1 |
| V852 Oph..............................| 16 25 22.16 | -24 30 13.7 | 2 |
| IRS 9.................................| 16 25 49.07 | -24 31 38.8 | 3 |
| ROXs 3.................................| 16 25 49.65 | -24 31 31.7 | 4 |
| ROXs 4/IRS 10...........................| 16 25 50.53 | -24 39 14.3 | 1, 3, 4 |
| IRS 4/ROXs 6/SRB 4........................| 16 25 56.18 | -24 20 48.2 | 3, 4, 5 |
| DOAr 7/IRS 13/GSS 20*..................| 16 25 57.54 | -24 30 31.7 | 1, 3; IRS 11 is 25705 away |
| ROXs 8/DoAr 21/GSS 23.................| 16 26 03.05 | -24 23 01.63 | 1, 3, 4, 5 |
| GSS 25/SRB 3...........................| 16 26 09.33 | -24 34 12.1 | 3, 4 |
| GSS 26.................................| 16 26 10.35 | -24 20 54.7 | 3 |
| GSS 29.................................| 16 26 16.87 | -24 22 23.0 | 4 |
| ROXs 10A/DoAr 24........................| 16 26 17.09 | -24 20 21.4 | 2, 5 |
| VSSG 1/Elias 20........................| 16 26 18.89 | -24 28 19.6 | 3 |
| GSS 30 IRS 1/Elias 21c...................| 16 26 21.42 | -24 23 02.3 | 3 |
| DoAr 25/GY 17...........................| 16 26 23.69 | -24 43 14.0 | 3 |
| ROXs 9A.................................| 16 26 23.99 | -25 47 16.1 | 2 |
| Elias 24'/WSB 31........................| 16 26 24.09 | -24 16 13.3 | 3 |
| ROXs 9B.................................| 16 26 30.72 | -25 43 39.8 | 2 |
| ROXs 9C.................................| 16 26 37.95 | -25 45 12.8 | 2 |
| WSB 37/GY 93............................| 16 26 41.28 | -24 40 17.8 | 3 |
| WLB 16.................................| 16 27 02.35 | -24 37 27.2 | 3, 4 |
| WLB 15/Elias 29........................| 16 27 09.44 | -24 37 18.7 | 3, 4 |
| GY 224.................................| 16 27 11.20 | -24 40 46.6 | 6 |
| WL 19.................................| 16 27 11.73 | -24 38 31.9 | 6 |
| WL 4.................................| 16 27 18.50 | -24 29 05.9 | 3 |
| VSSG 22.................................| 16 27 22.92 | -24 17 57.3 | 3 |
| IRS 48.................................| 16 27 37.18 | -24 30 35.2 | 3, 4 |
| IRS 32b/GY 235c.........................| 16 27 13.84 | -24 43 31.6 | 4 |
| GY 292.................................| 16 27 33.11 | -24 41 15.1 | 2 |
| IRS 50.................................| 16 27 38.12 | -24 30 43.1 | 3 |
| ROXs 35A...............................| 16 27 38.31 | -23 57 32.9 | 2 |
| IRS 49.................................| 16 27 38.31 | -24 36 58.7 | 3, 4 |
| WSB 52/GY 314...........................| 16 27 39.43 | -24 39 15.5 | 2, 4 |
| IRS 51.................................| 16 27 39.83 | -24 43 14.9 | 3, 4, 6 |
| IRS 56.................................| 16 27 50.72 | -24 48 21.4 | 4 |
| IRS 54.................................| 16 27 51.79 | -24 31 45.7 | 3 |
| SR 10.................................| 16 27 55.56 | -24 26 18.1 | 3, 4 |
| WSB 60.................................| 16 28 16.51 | -24 36 58.0 | 3, 4 |
| WSB 63.................................| 16 28 54.09 | -24 47 44.2 | 4 |
| WSB 67c.................................| 16 30 23.31 | -24 54 16.2 | 4 |
| ROXs 39b...............................| 16 30 35.6 | -24 34 15.0 | 1 |
| ROXs 40.................................| 16 30 51.51 | -24 11 34.0 | 2 |
| WSB 69A.................................| 16 31 04.37 | -24 04 33.3 | 2 |
| WSB 69B.................................| 16 31 05.17 | -24 04 40.3 | 2 |
| ROXs 44/Haro 1-16........................| 16 31 33.45 | -24 27 37.1 | 2, 4 |
| IRS 63.................................| 16 31 35.67 | -24 01 29.3 | 6 |
| IRAS 16289−2457..........................| 16 31 54.74 | -25 03 23.8 | 2 |
| IRS 67.................................| 16 32 01.01 | -24 56 41.9 | 6 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* Coordinates from SIMBAD database.

Wavelength L/2300 km s−1; see Ageorges et al. 1997.

GSS 30 IRS 1 coordinates are from Zhang, Wootten, & Ho 1997.

Verifications of association membership remain to be established; see Simon et al. 1995.

Coordinates for WSB 67 are precessed from Simon et al. 1995.

References.—(1) Ageorges et al. 1997; (2) this work; (3) Costa et al. 2000; (4) Simon et al. 1995; (5) Ghez et al. 1993; (6) Haisch et al. 2002.

and found it to be single are listed in column (4). In constructing the table, we were careful not to count the same target object multiple times, even when referred to by different names in the different surveys.

Comparison of the data presented in Tables 3 and 4 for the ρ Oph cloud core with previous work on ρ Oph, other star-forming regions, and the main sequence requires determination of the binary fraction, $F_b = (B + T + Q)/$
(S + B + T + Q), and the companion star fraction, \( F_c = (B + 2T + 3Q)/(S + B + T + Q) \), where \( S \) is the number of single stars, \( B \) is the number of binary systems, \( T \) is the number of triple systems, and \( Q \) is the number of quadruple systems in the survey sample. These definitions assume that there is no restriction on magnitude differences between companions, or on separations between companions, an assumption that is clearly unattainable in practice.

The quantity that one can measure is a restricted binary fraction, which is the binary fraction restricted to a stated magnitude difference between primaries and their secondaries and in a given (physical, not angular) separation range. Hopefully, the stated restriction guarantees a complete sample, i.e., that all binaries within the given separation and magnitude difference ranges would be detected by the given survey. Such a complete sample may be defined for a single, given survey but cannot be determined a posteriori, when comparing data sets published by various authors. The best we can do is to choose restrictions that are the most likely to result in a complete sample over all the published studies.

Given all these caveats, our restricted sample from Tables 3 and 4 will encompass \( \Delta K \sim 3 \) and \( 0.1 \leq \Delta \Theta \leq 1.1 \) for the \( \rho \) Oph cloud core. This sample is restricted to targets that were searched for multiplicity via high-resolution, near-infrared techniques only (e.g., by any of the six surveys of Ageorges et al. 1997; Costa et al. 2000; Ghez et al. 1993; Haisch et al. 2002; Simon et al. 1995; this work). If we restrict our attention to the subsample of Table 3 searched for multiplicity by only these six surveys (32 of the 49 systems listed), then among this subsample there are 19 systems with at least one separation in the \( 0.1 \leq \Delta \Theta \leq 1.1 \) range. Of the 32 multiple systems listed in Table 3 that were surveyed by the above-listed six surveys, there remain 13 systems with no separations in the restricted range. In addition, there are 48 distinct targets searched by these six surveys, which were found to be single (listed in Table 4). Thus, the restricted binary fraction is \( 19/(19 + 13 + 48) = 24\% \pm 11\% \). We note parenthetically that when a binary is found in this restricted \( 0.1 \leq \Delta \Theta \leq 1.1 \) separation range, if it is part of a wider separation triple or quadruple, we still consider the larger multiple system as a single target for counting purposes. Were we to count targets that are separated by \( \geq 1.1 \) as individual targets for counting purposes, then we would get a lower value for the restricted binary fraction for \( \rho \) Oph. We therefore adopt the value of \( 24\% \pm 11\% \) \( 19/(32 + 48) \) as the restricted binary fraction, \( F_{br} \), for the \( \rho \) Oph pre–main-sequence population in the \( \sim 0.1 \) to \( 1.1 \) range.

Ghez et al. (1993) define their complete sample by the restrictions \( \Delta K \leq 2, 0.1 \leq \Theta \leq 1.8 \) for Taurus and \( \Delta K \leq 2, 0.1 \leq \Theta \leq 1.6 \) for Sco-Oph, since they assumed distances of 140 and 160 pc to Taurus and Ophiuchus, respectively, and the restriction on angular separation was meant as a restriction on true, projected, physical separations, corresponding to 16–252 AU in that study. The restricted binary star frequency among Sco-Oph targets, with the restrictions as defined by Ghez et al. (1993) for Sco-Oph, was 29\% \pm 12\% from a sample of 21 targets. The restricted binary star fraction for this same set of constraints for Taurus was found to be 37\% \pm 9\% from the 43 targets in their complete sample. Our newly derived value of 24\% \pm 11\% from 80 Ophiuchus-only targets, restricted to a somewhat smaller physical separation range, but to a similar magnitude difference range between primaries and secondaries, is consistent, within the errors, with the restricted binary star frequency among the pre–main-sequence populations of Ophiuchus and Taurus being identical.

In a related study of X-ray–selected T Tau stars in the Sco-Cen OB association, which is at the same distance as the Ophiuchus cloud core, Köhler et al. (2000) used both near-infrared speckle and near-infrared direct imaging techniques in order to achieve completeness limits for companions in the \( 0.1 \leq \Delta \Theta \leq 0.6 \) and \( \Delta K \leq 2.5 \) mag ranges. They found 27 binaries and two triples from 88 targets, corresponding to 33\% \pm 11\% for their restricted binary fraction, \( F_{br} = (27 + 2)/88 \), and 35\% \pm 11\% for their restricted companion fraction, \( F_{cr} = (27 + 2 \times 2)/88 \), after correcting for contamination by background objects and for X-ray selection bias. Although at first glance the restricted binary star frequency among the Sco-Cen and Ophiuchus samples is consistent with being identical within the errors, one must bear in mind that the separation range of \( 2'' \leq a \leq 6'' \) was not sampled in Ophiuchus, whereas it was sampled in Sco-Cen.

We note that the physical separation range to which our discussion of the Ophiuchus and Taurus samples was restricted would correspond to an angular separation range of \( 0.03 \leq a \leq 0.37 \) at the distance to the Orion star-forming region. This angular separation range, although accessible with the largest (10 m diameter) ground-based telescopes equipped with adaptive optics, has not yet been explored toward Orion (Beck et al. 2003; Simon, Close, & Beck 1999). Therefore, at present, no direct comparison can be made between the restricted binary fractions in \( \rho \) Oph and Taurus, on the one hand, and Orion, on the other.

Comparison of the \( \rho \) Oph multiplicity fraction with that of the main sequence requires calculation of the companion star fraction, \( F_c \), in this separation range. For the same restrictions (\( \sim 0.1 \) to \( \sim 1.1, \Delta K \leq 3 \)), as above, the restricted companion star fraction derived from the data presented in Tables 3 and 4, is \( 24\% \pm 11\% \) for \( \rho \) Oph. This fraction is arrived at by counting three triples, V853, ROXs 42C, and ROXs 47A, from Table 3 as binaries, since the restriction on angular separations excludes some of the multiple components that are detected in these systems. The main-sequence companion star fraction in the projected physical separation range, 16–252 AU, (corresponding to angular separations \( 0.1 \leq \Theta \leq 1.8 \)) at an assumed 140 pc distance to \( \rho \) Oph is \( 16\% \pm 3\% \) for stars in the 0.8 \( M_\odot \leq M \leq 1.3 M_\odot \) mass range (Duquennoy & Mayor 1991) and 12\% \pm 4\% for lower mass \( M_\odot \) dwarfs (Fischer & Marcy 1992). For purposes of comparison with the main-sequence results, it must be borne in mind that the restricted companion star fraction derived for \( \rho \) Oph above is, a strict lower limit in the sense that we imposed an additional constraint, that of \( \Delta K \leq 3 \) on our sample, whereas no component flux ratio limits were imposed on the samples used to derive the main-sequence–restricted companion fractions. An overabundance of multiple systems among the pre–main-sequence population of Ophiuchus relative to the main sequence over this restricted separation range is not yet a statistically significant (3 \( \sigma \)) result, however.

Future multiplicity surveys of the \( \rho \) Oph pre–main-sequence population at larger component separations, when combined with the data presented here, would decide the question of whether we are observing a true overabundance of multiple systems among recently formed stars relative to
the main sequence, or if we are witnessing the evolution of binary separations with time.

4.3. IRS 43, IRS 44, and IRS 51

As alluded to in § 4.2, often several sets of authors have searched the same target for multiplicity (viz., Table 4). In general, search results reported by different sets of authors, but obtained with techniques sensitive to similar magnitude differences and to similar size scales, agree well. However, there are three objects, IRS 43, IRS 44, and IRS 51, for which results amongst different authors, and even among the same authors, give conflicting or confusing results.

IRS 43 (YLW 15A) is an unusual object in ρ Oph, because it is by far the strongest X-ray source, exhibiting powerful X-ray flaring activity (Grosso et al. 1997; Montmerle et al. 2000; Tsuboi et al. 2000). A VLA 3.6 cm radio map of IRS 43 resolved two sources: VLA 1, a resolved, thermal jet, and VLA 2, a point source, positionally coincident (to within ±0.2") with the bright near-infrared source, IRS 43 (Girart, Rodriguez, & Curiel 2000). Ground-based, mid-infrared imaging at the Keck II telescope with JPL’s MIRLIN camera found a 0.51", position angle (P.A.) = 332.7" binary associated with IRS 43, similar in appearance to the double 3.6 cm source (Haisch et al. 2002). However, ground-based near-IR measurements detected only a single NIR source (to K < 12), associated with VLA 2, the southeastern 10 μm component (Simon et al. 1995; Costa et al. 2000). IRS 43 was reported as a single source with NICMOS imaging through the 1.1 and 1.6 μm filters (Allen et al. 2002), but “two pointlike sources clearly showing the NICMOS diffraction pattern” are reported by Terebey et al. (2001), who reached a 2000:1 dynamic range using the 2.05 μm filter. Nevertheless, Terebey et al. (2001) classify IRS 43 as a single object, with no further information given.

IRS 44 (YLW 16A) is, similarly, not resolved by ground-based measurements (Simon et al. 1995; Costa et al. 2000; Haisch et al. 2002). Allen et al. (2002) detect two nonpoint sources, separated by 0.25" at P.A. = 270° with a flux ratio of 1.5 at 1.1 μm and 1.1 at 1.6 μm in their NICMOS images of IRS 44. They interpret this as scattered light from possibly a star/disk/envelope system. Terebey et al. (2001), on the other hand, report the detection of two point sources, at a separation of 0.27" at P.A. = 81°, with the primary detected in all three (F160W, F187W, and F205W) NICMOS images, and the secondary detected only at the longest, 2.05 μm, wavelength.

IRS 51, although found to be a point source by Simon et al. (1995) and by Costa et al. (2000), was found to be extended in H, K, and L shift-and-add imaging by Haisch et al. (2002). Whereas the near-infrared images presented by Haisch et al. (2002) are consistent with a secondary at P.A. = 10° at 1.5" separation, the mid-infrared image of the same object, at similarly high angular resolution, consists of extended emission, with an emission “knot” at just 0.7" separation at P.A. = 15°. Clearly, the source of the extended near- and mid-infrared emission surrounding this object deserves further study.

5. SUMMARY

1. We have carried out a new, near-infrared, speckle imaging survey of 19 pre–main-sequence objects in ρ Oph, of which four are binary, and one is a newly discovered triple system.

2. We have tabulated all the close binaries known in the ρ Oph cloud core, as well as all of the ρ Oph cloud members searched for multiplicity, but found to be single, by various high angular resolution, near-infrared techniques.

3. Synthesis of the multiplicity data presented here results in the determination of 24% ± 11% for the restricted binary fraction of the Ophiuchus pre–main-sequence population in the ~ 0.1–1.7" range. This can be compared with the 37% ± 9% restricted binary fraction found in the Taurus pre–main-sequence population over a ΔK ≤ 2, 0.1" ≤ Θ ≤ 1.8" range. Future adaptive optics observations toward Orion with 10 m aperture telescopes, which can sample the 0.03 ≤ 0.34 angular separation range, will allow a direct comparison with the restricted binary fraction in Orion in the projected physical separation range, 16–154 AU.

4. The observed restricted companion fraction derived from the data presented here is also 24% ± 11% for ρ Oph in a range restricted to ~ 0.1–1.7" separations, and to magnitude differences, ΔK ≤ 3. Due to the magnitude difference constraint imposed on the ρ Oph sample, 24% ± 11% represents a strict lower limit to the true restricted companion fraction of ρ Oph in this separation range. In the physical separation range of 16–252 AU, the true restricted companion fraction for the main sequence is 16% ± 3% for stars in the 0.8 M⊙ ≤ M ≤ 1.3 M⊙ mass range (Duquennoy & Mayor 1991), and 12% ± 4% for lower mass, main-sequence M dwarfs (Fischer & Marcy 1992).

5. Larger surveys for companions among the ρ Oph association members are required to definitively establish (to σ) the overabundance of the companion fraction relative to that of the main sequence. Surveys for multiples at large separations in the ρ Oph population, corrected for background contamination, will help improve the statistics. Synthesis of multiplicity data from future surveys at all separations will decide whether it is the multiplicity fraction or the binary separation distribution that evolves with time from the pre–main-sequence to the main sequence.

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