A Luminous Infrared Companion in the Young Triple System
WL 20

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ABSTRACT

We present spatially resolved near-infrared and mid-infrared (1–25 $\mu$m) imaging of the WL 20 triple system in the nearby ($d = 125$ pc) $\rho$ Ophiuchi star-forming cloud core. We find WL 20 to be a new addition to the rare class of “infrared companion systems”, with WL 20:E and WL 20:W displaying Class II (T-Tauri star) spectral energy distributions (SEDs) and total luminosities of 0.61 and 0.39 $L_\odot$, respectively, and WL 20:S, the infrared companion, with a Class I (embedded protostellar) SED and a luminosity of 1.0–1.8 $L_\odot$. WL 20:S is found to be highly variable over timescales of years, to be extended (40 AU diameter) at mid-infrared wavelengths, and to be the source of the centimeter emission in the system.

The photospheric luminosities of 0.53 $L_\odot$ for WL 20:E and 0.35 $L_\odot$ for WL 20:W, estimated from our data, combined with existing, spatially resolved near-infrared spectroscopy, allow us to compare and test current pre-main-sequence evolutionary tracks. The most plausible, non-accreting tracks describing this system are those of d’Antona & Mazzitelli (1998). These tracks give an age of 2–2.5 $\times$ 10$^6$ yr and masses of 0.62–0.68 $M_\odot$ for WL 20:E and 0.51–0.55 $M_\odot$ for WL 20:W, respectively. The age and mass of WL 20:S cannot be well determined from the currently available data. WL 20:E and WL 20:W fall into the region of the H-R diagram in which sources may appear up to twice as old as they actually are using non-accreting tracks, a fact which may reconcile the co-existence of two T-Tauri stars with an embedded protostar in a triple system. The derived masses and observed projected separations of the components of the WL 20 triple system indicate that it is in an unstable dynamical configuration, and may therefore provide an example of dynamical evolution during the pre-main-sequence phase.

Subject headings: stars:formation — stars:pre-main-sequence — binaries:close — stars:individual(WL 20)

1. Introduction

The optically undetectable source, WL 20 (also known as BKL T J162715−243843 and GY 240, see Barsony et al. 1997, for other aliases), was discovered in a near-infrared (near-IR) bolometer survey of a 10$' \times$ 10$'$ region of self-absorbed $^{13}$CO emission in the $\rho$ Ophiuchi star-forming cloud (Willing & Lada 1983). Soon thereafter, WL 20 was
detected at 10 µm from ground-based observations (Lada & Wilking 1984), and at longer wavelengths in the pointed observations mode of the IRAS satellite, where it is referred to as YLW 11 (Young et al. 1986).

In the currently accepted classification scheme of young stellar objects (YSOs) devised by Lada (1987), WL 20 was one of the first sources to be identified as a Class I source (Wilking, Lada, & Young 1989). Empirically, Class I sources have broader than blackbody spectral energy distributions (SEDs), with rising 2–10 µm spectral slopes, $a > 0.3$ (where $a = \frac{d \log \lambda F_{\lambda}}{d \log \lambda}$). Theoretically, the SEDs of Class I sources are interpreted to correspond to a remnant infalling dust and gas envelope surrounding a central protostar+disk system (Adams, Lada, & Shu 1987). The more evolved Class II sources, with $-0.3 < a < -1.6$, are pre-main-sequence (PMS) star+disk systems that have dispersed their remnant infall envelopes.

With the advent of near-IR array detectors, WL 20 was soon resolved into a binary system at 2.2 µm using a pixel scale of 0′′.85 (Rieke, Ashok, & Boyle 1989) and first reported to have an east-west separation of $\approx 2′′.7$ from observations with a pixel scale of 0′′.78 (Barsony et al. 1989). This separation corresponds to $\approx 340$ AU for an adopted distance to the cloud of 125 pc.

We note that some confusion still exists as to the distance to the ρ Ophiuchi clouds, primarily due to many authors citing the distance to the adjacent Sco-Cen OB association instead. The distance to the Sco-Cen OB association has been determined to be 160±10 pc photometrically (Whittet 1974) or 145 pc astrometrically (de Zeeuw et al. 1999). By contrast, the distance to the ρ Ophiuchi cloud itself has been determined to be 125±25 pc from detailed kinematic studies of the cloud gas (de Geus, de Zeeuw, & Lub 1989; de Geus 1992), and, more recently, by a study of Hipparcos parallaxes and Tycho $B - V$ colors of stars of Classes III & V, which show an abrupt rise in reddening at $d = 120$ pc, as expected for a molecular cloud (Knuide & Hog 1998). We therefore adopt a distance of 125 pc to the cloud in this paper.

The first indication that WL 20 is a triple system came from a deep ProtoCAM survey to identify near-IR counterparts of centimeter continuum sources in the ρ Ophiuchi cloud core (Strom et al. 1995). The VLA source identified with WL 20 is known as LFAM 30, and was imaged at 6 cm with an 11″×5″ beam (Leous et al. 1991). With the sensitive ProtoCAM images acquired at a pixel scale of 0′′.20, a third and weakest 2.2 µm component of the system was easily identified, and designated as “30S” (for the Southern component of LFAM 30), whereas the components of the previously known near-IR binary are referred to as “30E” and “30W” by these authors (Strom et al. 1995). With 30E as the positional reference, 30W is quoted at a separation of 3′′.3 at P.A. 269°, and 30S at a separation of 3′′.9 at P.A. 232°.

Near-IR spectra of the two brighter K components of the WL 20 triple system, WL 20:E ($K = 10.13$) and WL 20:W ($K = 10.40$) were presented as part of a spectroscopic survey of YSOs with $K < 10.5$ in ρ Oph (Greene & Lada 1996). The near-IR spectra of both WL 20:E & W were found to be consistent with those of other Class II sources, with a K–M spectral type established for WL 20:E, and a more precise K7–M0 spectral type determination for WL 20:W, due to the less severe continuum veiling in its spectrum (Greene & Meyer 1995). At their assumed distance of 160 pc, WL 20:E was determined to have a bolometric luminosity, $L_{bol} = 0.4L_\odot$, through $A_V = 15.4$, whereas WL 20:W was determined to have $L_{bol} = 1.7L_\odot$ through $A_V = 18.1$. Continuum veiling in the spectrum of WL 20:E precluded its placement on the H-R diagram, whereas the lesser veiling in the spectrum of WL 20:W allowed a mass estimate of 0.3 $M_\odot$ from its location along a $3 \times 10^5$ yr pre-main-sequence isochrone (Greene & Meyer 1995).

A more recent spectroscopic survey of near-IR sources in the ρ Ophiuchi core including many sources as faint as $K \sim 12$, was obtained at higher spectral resolution ($R = 1200$) than the previously published surveys (with $R \leq 1000$), allowing for significantly improved classifications for G through M spectral types (Luhman & Rieke 1999). These authors assigned a K6 spectral type to WL 20:E (GY 240B), with a bolometric luminosity of 0.55 $L_\odot$, and an M0 spectral type to WL 20:W (GY 240A) with $L_{bol} = 1.4L_\odot$ (they also assumed a distance of 160 pc). Both sources were found to have a foreground extinction of $A_V = 16.3$. WL 20:S, with $K \sim 12.6$, was excluded from this survey as well, due to its relative dimness at near-IR wavelengths.

Interestingly, the discrepancy between the Class I SED classification of WL 20 on the one hand, and its near-IR Class II spectroscopic classifications on the other, has not been remarked upon previously. This inconsistency can only be addressed by producing spatially resolved SEDs of the individual components of this triple system. Until now, the highest spatial resolution photometry of
WL 20 longward of 4.8 μm has been through a 6–8′′ aperture—confusing all three components (Lada & Wilking 1984). In order to better constrain the properties of WL 20:S, and of the triple system of which it is a member, we have obtained new, unprecedentedly high (sub-arcsecond) spatial resolution, ground-based mid-IR images of the WL 20 system, at six separate wavelengths spanning the 8–25 μm atmospheric window. Additionally, we present spatially resolved near-IR imaging of this triple system. Finally, we have performed careful astrometry, allowing us identify the source of the centimeter continuum emission.

2. Observations

All mid-infrared images were obtained with MIRLIN, JPL’s 128×128 pixel Si:As camera. Diffraction-limited images were obtained on the nights of 1996 April 24 at the Palomar 5-m telescope, 1998 March 13–14 on the Keck II 10-m telescope, and 2000 June 16 at NASA’s 3-m Infrared Telescope Facility (IRTF). Pixel scales of MIRLIN were 0′′15 at Palomar, 0′′138 at Keck II, and 0′′475 at the IRTF. Observations at Palomar and the IRTF were made with the broadband N filter (λ = 10.8 μm, Δλ = 5.7 μm). For reference, the full-width at half maximum (FWHM) of a diffraction limited image at N-band is 0′′47 at Palomar and 0′′78 at the IRTF. Observations at the Keck II telescope were made with narrower filters, with central wavelengths (bandwidths) of 7.9 μm (0.76 μm), 10.3 μm (1.01 μm), 12.5 μm (1.16 μm), 17.9 μm (2.00 μm), 20.8 μm (1.65 μm), and 24.5 μm (0.76 μm); corresponding FWHMs range from 0′′78 at 7.9 μm to 0′′53 at 24.5 μm.

The flux of WL 20 at each wavelength was determined by comparison with α Sco at Palomar, and at Keck II with a combination of α Boo, α CMa, α CrB, α Hya, β Leo, and σ Sco, the last of which proved to be an easily resolved 0′′45 binary. The weather at the IRTF was sufficiently poor that no flux standards were observed. Data were obtained with traditional mid-IR chopping and nodding techniques. The raw images were background-subtracted, shifted, and coadded with our in-house IDL routine “MAC” (Match-and-Combine). Photometry for the standard stars was performed in 2′′5 and 2′′3 diameter apertures for the Palomar and Keck II data, respectively, when the separation between components was adequate (as determined by the intensity contours falling to zero between the sources) and by a combination of aperture summar-
3. Results

3.1. Imaging, Photometry, and SEDs

We present diffraction-limited (∼0\textquotesingle25 resolution at 10 \(\mu\)m) mid-infrared images of the WL 20 triple system acquired with MIRLIN at the Keck II telescope, along with representative shorter wavelength images acquired with ProtoCAM at the IRTF in Figure 1. We list the source separations and position angles derived from mean positions obtained from the 7.9, 10.3, and 12.5 \(\mu\)m images in Table 1. The individual components of the WL 20 triple system are labeled in Figure 1e (the 10.3 \(\mu\)m image). It is evident from inspection of Figure 1 that whereas WL 20:S is the weakest source of the system at the shortest wavelengths, it gradually brightens towards the longer wavelengths, just as its companions to the north are dimming. Eventually, WL 20:S dominates the system luminosity at the longest wavelengths (17.9, 20.8, and 24.5 \(\mu\)m).

We have used a combination of software aperture summation and point-spread function fitting to obtain photometric information for each component of the WL 20 system individually. Fluxes derived from the new data presented here, as well as all known previously published values, are listed in Table 2.

The resulting spectral energy distributions (SEDs) are presented in Figures 2 and 3. The SEDs for E and W (Figure 2a) are consistent with their being reddened Class II sources with modest excesses at long wavelengths, in agreement with the near-IR spectroscopic results. The spectral slopes, \(a = -0.79\) for WL 20:E, and \(a = -0.91\) for WL 20:W, are as expected for Class II sources. In fact, the shape of the SED of WL 20:W is quite close to a reddened blackbody in the near-IR (i.e., a small near-IR excess, though the excess at mid-IR wavelengths is substantially larger). Thus it is possible that the circumstellar material around WL 20:W may be optically thin enough for silicate emission to be present. Comparison of the 10.3 \(\mu\)m fluxes (near the center of the silicate feature) with the “continuum” fluxes at 7.9 and 12.5 \(\mu\)m suggests a factor of ∼2 excess at 10.3 \(\mu\)m in WL 20:W with respect to that anticipated from the shape of WL 20:E’s SED. Our single data point is not sufficiently compelling (though it is robust) to warrant a large discussion of silicate emission here, but future spatially-resolved mid-IR spectroscopy should address in fine detail the nature of the dust emission and absorption in these Class II sources.

The SED of WL 20:S (Figure 2b), however, is that of a Class I source, with \(a = +1.44\). Given that there is a generally continuous slope between our ground-based mid-IR data for WL 20:S and the far-infrared and millimeter fluxes for the entire WL 20 system, we have attributed all the longer wavelength flux observed in this system to WL 20:S (Figure 3). For the case of the millimeter emission, this assumption may be tested by future interferometric observations.

We color-correct the IRAS fluxes for this source in order to make the best luminosity estimate possible. We use our narrowband observations with MIRLIN at 12.5 and 24.5 \(\mu\)m along with others’ 850 \(\mu\)m and 1.3 mm observations to constrain the shape of the far-IR SED so the color-correction terms may be estimated. The spectral slope implied by all the narrowband mid-IR data follows a \(F_\nu \propto \nu^{-3}\).
Table 1: Relative position of the three components.

<table>
<thead>
<tr>
<th>Pair with respect to</th>
<th>Separation (arcsec)</th>
<th>Separation (AU)</th>
<th>Position Angle (°)</th>
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<tr>
<td>W with respect to E</td>
<td>3.17±0.01</td>
<td>400</td>
<td>270.1±0.3</td>
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<tr>
<td>S with respect to E</td>
<td>3.66±0.03</td>
<td>460</td>
<td>232.2±0.2</td>
</tr>
<tr>
<td>S with respect to W</td>
<td>2.26±0.02</td>
<td>280</td>
<td>173.0±0.3</td>
</tr>
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</table>

Table 2: Fluxes for the WL 20 components.

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
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<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>This Work</td>
<td>SKS</td>
</tr>
<tr>
<td></td>
<td>E W S E W S</td>
<td>Total</td>
</tr>
<tr>
<td>1.29</td>
<td>3.8* 3.0* 0.03*</td>
<td>4.2</td>
</tr>
<tr>
<td>1.67</td>
<td>32.7* 25.6* 0.79*</td>
<td>30.7</td>
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<tr>
<td>2.23</td>
<td>87.1* 61.0* 5.9*</td>
<td>57.1</td>
</tr>
<tr>
<td>3.55</td>
<td>123.2* 69.7* 15.3*</td>
<td>208*</td>
</tr>
<tr>
<td>3.82</td>
<td>137.7* 70.3* 18.6*</td>
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</tr>
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</tr>
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<tr>
<td>1300</td>
<td></td>
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</tr>
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</table>

*Non-photometric.

REFERENCES.—a) Strom et al. (1995); b) Wilking & Lada (1983); c) Wilking et al. (2000); d) Lada & Wilking (1984); e) Young et al. (1986)—data have been color-corrected as described in the text; f) Ward-Thompson & Kirk (2000); g) Andrés & Montmerle (1994)

power law over this range, so we deredden the 12 and 25 µm fluxes according to that rule from the IRAS Explanatory Supplement (Beichman et al. 1988), dividing them by factors of 0.91 and 0.89, respectively. The SED clearly peaks in the vicinity of 60 µm (or at least does not rise significantly throughout the entire 45–80 µm passband). We therefore fit the 60, 850, and 1300 µm data with a ∼80 K greybody. In fact, the 60 µm color correction at this temperature is quite small (divide by 0.97) and is not very sensitive to modest excursions in temperature (60–120 K), so that even using the uncorrected flux would be adequate. The resulting data show the usual factor of 2–3 excess of the IRAS measured flux vs. the ground-based data (e.g., Lada & Wilking 1984).

3.2. Luminosities of the Individual Components of WL 20

We compute the luminosities of each Class II component of the WL 20 system (E and W) by integrating under the curves displayed in Figure 4. The data points from 1.2 ≤ λ ≤ 18 µm have been dereddened using a Draine & Lee (1984) extinction curve assuming AV = 16.3 (Luhman & Rieke 1999). Though we assume AV = 16.3, we can rule out AV > 18 from our data since the near-IR data then have a slope steeper than a blackbody, and AV < 15 can be ruled out as the near-IR data would then be too red to be consistent with the flux from a ∼4000 K photosphere. We use a power law extrapolation from 18 through 1300 microns consistent with the spectral slope from 3–18 µm (Fν ∝ ν^0.45) to
estimate the source fluxes at far-infrared through millimeter wavelengths. Other extrapolations for the fluxes from 18 \( \mu \text{m} \) to longer wavelengths may be used (e.g. no flux at all past 18 \( \mu \text{m} \), or even a constant flux between 18 and 1300 \( \mu \text{m} \)), but none change the estimated luminosity more than 2\%, since the majority of the energy is emitted at shorter wavelengths.

A strict lower limit to the source luminosities, the “infrared” luminosities, are arrived at by integrating under the dereddened 1–18 \( \mu \text{m} \) data points and the long wavelength extrapolation described above using simple trapezoidal integration. We find an infrared luminosity of 0.26 \( L_\odot \) for WL 20:E, and 0.17 \( L_\odot \) for WL 20:W. We have used our near-IR photometry to compute the luminosity rather than that of Strom et al. (1995) since this provides better continuity with the mid-IR data. However, use of the Strom et al. (1995) near-IR data reduces our luminosity estimates by only 0.03 \( L_\odot \) for each component.

To obtain a more accurate value of the total luminosity of each component, however, we scale a blackbody spectrum from 0.1–1.2 \( \mu \text{m} \) at the effective temperatures found by Luhman & Rieke (1999) to match the observed infrared data values. Luhman & Rieke (1999) found temperatures of 4205 K for WL 20:E and 3850 K for WL 20:W. We then integrate under this blackbody curve in addition to
Fig. 4.— Luminosity determinations for the three components of the WL 20 system. The data for the three components, along with the curves used to obtain the best luminosity estimates, are plotted. The data for WL 20:W have been divided by two for clarity. The data for all three components have been dereddened by assuming an $A_V = 16.3$ foreground screen and a Draine & Lee (1984) extinction curve (solid lines). An non-dereddened curve for WL 20:S (dashed line) is also plotted for the case where all the extinction is local to the source and dereddening is not appropriate. The “model” curves for WL 20:E & W are represented directly by the data from 1–18 $\mu$m, a blackbody of the appropriate effective temperature (see the text) from 0.1 to 1.2 $\mu$m, and a power law beyond 18 $\mu$m. The curves for WL 20:S are composites of several blackbodies modified for extinction and dust emissivity. The curves for WL 20:S assume all far-IR and millimeter flux originate from WL 20:S; in the case that only 50% does (see the text), the 60 $\mu$m and millimeter points are reduced by a factor of two and the model curves > 40 $\mu$m are correspondingly reduced.

the infrared data points (the solid curves in Figure 4). This technique yields total luminosities of 0.61 $L_\odot$ for WL 20:E and 0.39 $L_\odot$ for WL 20:W. Integration of only the blackbody (over all wavelengths), which should approximate the emission of the photosphere without luminosity from the disk, yields 0.53 and 0.35 $L_\odot$, respectively. These values are appropriate for comparison with the pre-main sequence evolutionary models discussed in Section 4.2.

For WL 20:S, computing the luminosity is complicated by two issues: if and how to deredden the data, and how to partition the flux at far-IR and millimeter wavelengths where the sources are not resolved. With regard to dereddening, since no photospheric measurements are available, we can assume either that all the extinction is local and most of the near-IR photons are absorbed and reradiated in the far-IR where the extinction is much smaller, or that the same $A_V = 16.3$ foreground screen is present as for the other two components (and there is a correspondingly lower local extinction). Dereddening the data in the first case would “double count” the near-IR photons, while dereddening in the second is the correct procedure. However, since most of the energy is radiated in the mid-IR through millimeter regime where the extinction is small, the final luminosity estimate changes only 10% after dereddening.

As for the far-IR and millimeter fluxes, we can establish an upper bound on the luminosity by assuming that all the 60 $\mu$m IRAS flux from Young et al. (1986), the 850 $\mu$m flux from SCUBA (Ward-Thompson & Kirk 2000), and the 1.3 mm measurement from André & Montmerle (1994) originates from WL 20:S. As a lower bound, we assume that 50% of the flux originates from WL 20:S; this is consistent with the ground-based 12 and 25 $\mu$m points being roughly half the IRAS points. In either case, this necessarily implies that most of the dust in the WL 20 system surrounds WL 20:S. Also, the IRAS data presumably contain some contaminating flux from the nearby source WL 19; however, we know that WL 19 is quite faint with respect to WL 20 at 10.8 $\mu$m (factor of 5.6 fainter, Barsony, Ressler, & Casement 2000); therefore its effect on our luminosity estimate will be very small.

With all the above factors in mind, a simple trapezoidal integration of the WL 20:S fluxes yield a bolometric luminosity of 1.28 $L_\odot$ if all the extinction is local, and 1.40 $L_\odot$, if the data points are first dereddened for an $A_V = 16.3$ foreground screen. In both these instances, all the observed far-IR and millimeter fluxes were assigned to WL 20:S. If, instead, we assign only half the observed far-IR and millimeter flux to WL 20:S, the corresponding values for the luminosity become 0.84 $L_\odot$ and 0.95 $L_\odot$, respectively. Use of the Strom et al. (1995) near-IR data, instead of our near-IR data, increases these values by only 0.04 $L_\odot$.

To improve the above luminosity estimates for WL 20:S, given the coarseness of the trapezoidal integration algorithm and the sparseness of the data between 25 and 850 $\mu$m, where the SED peaks, we have constructed a smooth model curve which passes through all of the data points under which to integrate. This curve is constructed by assuming a
\( T_{\text{eff}} = 4000 \text{ K photosphere}, \) two blackbodies at \( T = 300 \text{ K} \) and \( T = 150 \text{ K} \) to represent the disk emission, and a modified \( T = 65 \text{ K} \) blackbody dust envelope with a \( \lambda^{-1} \) emissivity law. This model was created only to obtain a smooth curve which represents the SED of WL 20:S adequately for integration; it is not intended to be a physical description of the object. The corresponding derived luminosities for WL 20:S then become 1.71 \( L_{\odot} \) for the curve passing through the data points, 1.82 \( L_{\odot} \) for the curve dereddened by \( A_V = 16.3 \), assuming all of the far-IR and millimeter flux to originate from WL 20:S, and 1.04 \( L_{\odot} \) and 1.14 \( L_{\odot} \), respectively, for the case when only half the observed far-IR and millimeter fluxes are attributed to WL 20:S. Therefore, the true luminosity of WL 20:S lies somewhere between 1.0–1.8 \( L_{\odot} \), making this source the most luminous member of the system by a factor of \( \sim 2 \).

### 3.3. Variability of the Class I Source, WL 20:S

The slight discrepancy of the measured flux in the broadband-N (10.8 \( \mu m \)) filter for WL 20:S in the April 1996 Palomar data from the flux measured for this source with the the 10.3 \( \mu m \) silicate filter in the March 1998 Keck II data led us to examine the relative photometry of the components of the WL 20 system as a function of time (see Table 2). For this purpose, we replot the spatially resolved fluxes as intensity ratios with respect to the fluxes of component WL 20:E in Figure 5. The square symbols in this figure represent the previously published photometry from Strom et al. (1995) for data acquired in 1993 May. The circular symbols represent the relative photometry from our 1990 August ProtoCAM observations. (Because these are now relative ratios, the variations in the sky should divide out, and we believe the relative photometric errors are less than 5%.) The different epochs of MIRLIN observations are represented by stars and triangles. From this plot, it can be seen that whereas WL 20:W does not vary significantly over this wavelength range and timescale, WL 20:S varies greatly (factor of \( \sim 3 \)) in the near-IR and perhaps even changes the shape of its SED over the timescale of a few years.

Even at 10 \( \mu m \), the variations appear to be significant. Though our MIRLIN results show only a 25\% increase between 1996 and 1998, Lada & Wilking (1984) report a flux of 180 mJy for the entire system (all three components should have been contained in their 6 arcsec beam), whereas our total system flux from 1998 is 470 mJy. If we assume WL 20:E & W to be constant over this entire timespan, WL 20:S would have had a flux of only 60 mJy in 1981–3, resulting in a nearly 6-fold increase in 15 years.

Wilking et al. (2000) have also reported that WL 20 brightened from 160 to 290 mJy at 6.7 \( \mu m \) from 1996 through 1998. Piecing the observations together as well as possible, it seems that WL 20:S was in a low luminosity state in the early 1980s, brightened until \( \sim 1990 \), faded during the early 1990s, then has been increasing since the mid-1990s. Given the changing shape of the SED, it may be that as the accretion rate increases, both the luminosity and the local extinction rise, leading to large increases in the mid- and far-infrared and perhaps a decline in the near-infrared. Though much more temporal data is required to put these speculations on a firm footing, they seem plausible with the data in hand. We conclude that much of the total luminosity of WL 20:S is derived from accretion, and that the stellar luminosity cannot be directly determined from our data.
3.4. Astrometry and the Identification of LFAM 30 with WL 20:S

In their VLA survey of the ρ Ophiuchi cloud, Leous et al. (1991) found that a number of cluster members were radio emitters. One of their radio sources, LFAM 30, was associated with WL 20. However, until now, it had not been possible to identify which of the three components of the WL 20 system is responsible for the radio emission. In order to solve this problem, we obtained the astrometric data at the IRTF as described in Section 2. Assuming the mean position of LFAM 23 (WL 22) to be the zero point, we plot the offsets from the Leous et al. (1991) radio positions of these sources superimposed upon the N filter image of WL 20 in Figure 6. We therefore find that to within ±0.5 arcsec, LFAM 30 is coincident with WL 20:S.

WL 15 appears to be offset 1 arcsec east from the radio position. This is almost certainly due to the fact that the VLA coordinates were published only to the nearest 0.1 seconds of time, which is 1.4 arcsec on the sky at the declination of WL 20, so an offset of 1 arcsec is not unexpected. However, even if the total error were due to purely random pointing errors (which is unlikely given the small scatter for the other objects), the consistency of the radio offsets is sufficiently good that a correspondence between LFAM 30 and either E or W is ruled out.

3.5. Extended Mid-Infrared Structure of WL 20:S

During the course of obtaining PSF-fit fluxes for each component of the WL 20 system, we discovered that WL 20:S is extended at all mid-infrared wavelengths. In order to demonstrate this, we present images of the source after the subtraction of a scaled (to the peak intensity value) PSF, as well as intensity cross cuts along an E–W axis at 12.5, 17.9, 20.8, and 24.5 μm in Figures 7 and 8. Also shown for comparison are similarly obtained intensity cross-cuts of the flux standards used for the observations at each wavelength. Whereas the flux standards are unresolved point sources, as are the two Class II sources, WL 20:E & W, WL 20:S is seen to have a definite extent above that expected for a point source at each of the four plotted wavelengths. Somewhat surprisingly, the physical size of the emitting region is fairly constant at all four wavelengths (Table 3). The root-mean-square diameter (observed FWHM – PSF FWHM) is about 0.36±0.03 arcsec or 45±3 AU at the distance of WL 20. The source size does not increase significantly with increasing wavelength as is common in many Class I YSOs.

4. Discussion

4.1. WL 20: An “Infrared Companion” System

Infrared companion systems are young binary or multiple systems in which one of the members is significantly “redder” than the other members of the system. “Red” in this context means that the companion is often very faint or invisible at optical and perhaps even the shorter near-IR wavelengths, but very often dominates the luminosity of the system in the near- and mid-IR. A prototypical example of such a system is T Tau, with a projected separation
of 0\arcsec 73, corresponding to \( \sim 100 \) AU at the source. The northern component, T Tau N, exhibits a typical Class II spectrum. Although the SED of its companion, T Tau S, is much redder than that of a typical T Tauri star, suggesting localized, high extinction towards this source, the SED nevertheless peaks in the near-infrared (i.e., at \( \sim 5 \) \( \mu m \)), unlike a Class I SED, which peaks towards the far-infrared. T Tau S is detected only at wavelengths \( \geq 2.2 \) \( \mu m \), although its bolometric luminosity exceeds that of T Tau N by a factor of 2. Furthermore, T Tau S has been shown to be variable (at the level of 2 mag flux increases in the IR) over a 5 yr. time interval (Ghez et al. 1991; Gorham et al. 1992). Large near-IR variability is a characteristic trait of infrared companion systems (Mathieu 1994).

From our spatially resolved SEDs of the individual components of the WL 20 triple system, we can confidently assert WL 20 to be a newly identified member of the class of infrared companion systems. Table 4 lists the properties of each individual source derived from this work, with the spectral types and
The possibilities usually cited to explain such “infrared companion” systems include the following:

1. **A chance superposition of sources** It may be that WL 20:S is not physically associated with WL 20:E & W—it is a chance superposition and therefore WL 20:S can be in any evolutionary state relative to WL 20:E & W. We must stress that we cannot rule out this possibility based on currently available data. It is nevertheless well established that all three sources of the WL 20 system are YSOs, and therefore, all are associated with the ρ Ophiuchi cloud. The space density of embedded objects in this cloud (< 200/sq. degree, Kenyon et al. 1998) is low enough that finding three YSOs apparently separated by such small distances is very unlikely unless they are physically associated. Milli-arcsecond astrometry in the near-IR over a sufficiently long time interval could prove association definitively, either by showing the sources to have a common space motion or a definite orbital motion.

2. **A non-coplanar system where the IR companion is viewed “edge-on.”** It has recently been shown that a Class II source whose flared disk, with its surface heated by the stellar radiation field, could mimic the SED of a Class I source if the disk is in a nearly edge-on orientation to our line-of-sight (Chiang & Goldreich 1999). Indeed, we argue below that WL 20:S probably does have a flared disk, though the inclination is ~ 20° from edge-on. However, WL 20:S exhibits two phenomena common to IR companion systems that orientation effects cannot explain if it is simply another Class II object: at 1.0–1.8 \( L_\odot \) it is the dominant luminosity source in the system by a factor of two, and it is highly variable at both near- and mid-IR wavelengths. Neither of these would be expected if it were simply an extinguished sibling of the other two sources. We therefore consider this scenario unlikely.

3. **A younger age for the IR companion** It may be that WL 20:S formed significantly later than its companions, WL 20:E & WL 20:W. The projected separations between the components of the WL 20 system range from 280–460 AU (see Table 1). These separations correspond to sound crossing times of order ~ 1–2 \( \times 10^4 \) yr. Given that typical free-fall times of pre-collapse cores are of order \( 10^5 \) yr, the WL 20 system must have collapsed from a single cloud core. Based on this simple dynamical argument, it is highly unlikely that the individual components of the WL 20 system formed at different times.

4. **The objects are coeval; they are in a physical configuration and a certain phase of evolution in which most of the dust accretion is occurring on one of the objects, rather than all three.** This is the most plausible possibility for explaining the properties of the infrared companion, WL 20:S, in the WL 20 system. Indications are that the observed 1.3 mm flux from the WL 20 system is centered on the cm source (Andrè & Montmerle 1994), which we have shown is associated with WL 20:S (see Figure 6). The observed 1.3 mm flux of 95 mJy (Andrè & Montmerle 1994) translates to a circumstellar mass of 0.03 (0.06) \( M_\odot \), assuming optically thin emission from dust at \( T_d = 30 \) (50) K and \( \kappa_{1.3 \text{mm}} = 0.01 \text{ cm}^2 \text{ gm}^{-1} \). Infrared variability, such as observed in WL 20:S (see Figure 5), signals the presence of active accretion (e.g., Beck et al. 2000). The combined picture of this system is reminiscent of recent binary formation models (e.g., Bate & Bonnell 1997) in which one component can be bright and actively accreting relative to a less luminous secondary component, depending on the initial distribution of specific angular momentum in the collapsing protostellar envelope relative to the orbital angular momentum of the system. We
consider such a scenario to be the most likely one to explain the properties of the WL 20 triple system.

4.2. Testing Pre-Main-Sequence Tracks with the WL 20 System

To date, only a handful of pre-main-sequence binary or multiple systems have both spatially resolved spectroscopy and spatially resolved photometry over a wavelength range as broad as presented here (1–25 µm). With these data, we have been able to independently infer the luminosities of WL 20:E & W to significantly higher accuracy (∼ a few percent apart from systematic effects discussed below) than has been possible previously (see Table 4). This coeval system, with well-determined photospheric luminosities (Section 3.2) and effective temperatures, provides a stringent test to distinguish between currently available PMS evolutionary models. Figures 9a–d show isochrones (solid lines) and isomass (dashed lines) evolutionary tracks at the same scale for four different sets of PMS models, Baraffe et al. (1998), d’Antona & Mazzitelli (1998), Palla & Stahler (1999), and Siess et al. (2000), respectively. In each figure, the solid square denotes WL 20:E and the solid diamond denotes WL 20:W. Figure 9e shows the range of parameter space over which PMS tracks are customarily plotted (e.g., Palla & Stahler 1999). The solid square outline in this figure indicates the restricted range of parameter space plotted in Figures 9a–d, in order to emphasize the improved precision with which the different sets of tracks can be compared using the WL 20 data.

The two sources of systematic error in our luminosity determinations are the adopted distance, for which we are using the Hipparcos-determined value, and the adopted AV = 16.3. An error in the distance will move both sources up by the same amount in each panel of Figure 9: a distance of 140 pc will raise the points by ∼ 0.06 units in the log, or about one small tick mark along the luminosity axis. Similarly, a slightly greater value of extinction than the value of AV = 16.3 adopted here will also move the position of each source up vertically in Figure 9. With an extreme value of AV = 18, the luminosities are increased by ∼ 33%; 0.12 in the log, or 2.5 small tick mark(s).

From spatially resolved near-IR spectroscopy, Luhman & Rieke (1999) determine the spectrum of WL 20:W to be consistent with a photosphere of spectral type M2–K6, corresponding to a temperature range 3513 K ≤ Teff ≤ 4205 K, with an adopted spectral type of M0 (corresponding to Teff = 3850 K). The same authors assign a K6 (Teff = 4205 K) spectral type to WL 20:E, with possible spectral types in the range K5–K7, corresponding to 4060 K ≤ Teff ≤ 4350 K. In Figure 9, we indicate the possible effective temperature range for each source by the horizontal error bars.

Inspection of Figure 9 shows that none of the models rule out WL 20:E & W being a coeval pair, within the allowable errors in spectral type for each source. However, the derived ages and masses differ amongst the models. The d’Antona & Mazzitelli (1998) tracks yield a system age of ∼ 2.0–2.5 × 106 yr, with a mass of 0.62–0.68 M⊙ for WL 20:E and a mass of 0.51–0.55 M⊙ for WL 20:W. All the other models yield a system age twice as old: 4–5 × 106 yr. For an age of 4 × 106 yr, the Baraffe et al. (1998) models yield masses of 0.86 M⊙ for WL 20:E and 0.68 M⊙ for WL 20:W, respectively. The Palla & Stahler (1999) tracks yield a coeval system age of 5 × 106 yr, with masses of 0.83 M⊙ for WL 20:E and 0.70 M⊙ for WL 20:W. Similarly, the Siess et al. (2000) tracks yield a coeval system age of 5 × 106 yr, with masses of 0.85 M⊙ for WL 20:E and ∼ 0.65 M⊙ for WL 20:W.

Of the two possible ages for this system, 4–5 × 106 yr or 2.0–2.5 × 106 yr, the younger age is the more plausible one, especially when we consider that WL 20:S, which appears to be a Class I object, is also part of this system. Based on statistical arguments, Class I objects are generally thought to be just a few × 106 yr old (Wilking, Lada, & Young 1989), maybe 8 × 106 yr at most (Kenyon et al. 1990). Previous statistical studies have ignored the systematic effects introduced by unresolved binary/multiple systems, however, which have the effect of making a source appear brighter (and therefore, judged to be younger), than is, in fact, the case. Such an effect can result in derived ages of a factor of two too young (White 1999), so that the oldest Class I sources may be of order 1.6 × 106 yr old, just about consistent with the 1.8 × 106 yr old system age derived from the d’Antona & Mazzitelli (1998) and Tout et al. (1999) tracks.

Very recently, pre-main-sequence tracks which include the effects of accretion on the models have been calculated (Tout et al. 1999). These authors provide the magnitude of the errors possible when one derives ages and masses of PMS objects from evolutionary tracks that ignore accretion, such as the ones discussed above. In particular, placement of WL 20:E & W on their Figure 14, shows that the derived age from the other tracks, including those of
Fig. 9.— See next page for caption.
Fig. 9.— Testing pre-main-sequence evolutionary tracks with the WL 20 system. The first four panels of this figure display four separate sets of pre-main-sequence evolutionary tracks over magnified luminosity and temperature ranges. The stringency with which we are testing and comparing these models is illustrated by the outlined box in Figure 9e, which indicates the parameter ranges of the plots presented in Figures 9a–d compared with the scale of previously plotted pre-main-sequence tracks (e.g., Palla & Stahler 1999). In all the panels, solid lines indicate isochrones, dashed lines indicate isomass tracks, the filled square represents WL 20:E, and the filled triangle represents WL 20:W. Figure 9a shows the Baraffe et al. (1998) tracks. The youngest coeval system age still within the errors is $4 \times 10^6$ yr. Figure 9b shows the d’Antona & Mazzitelli (1998) tracks. The adopted temperatures and luminosities of WL 20:E & W are consistent with an age of $2.0–2.5 \times 10^6$ yr. This is the most plausible (youngest) system age given by any of the tracks presented here, as discussed in the text. Figure 9c shows the Palla & Stahler (1999) tracks. The youngest system age, still within the data errors, and subject to the coevality constraint is $\sim 5 \times 10^6$ yr. Figure 9d shows the Siess et al. (2000) tracks. The youngest system age, still within the data errors, and subject to the coevality constraint is $\sim 5 \times 10^6$ yr. Figure 9e shows the usual scale to which pre-main-sequence tracks are plotted. The rectangular area outlines the plot limits of Figures 9a–d, to highlight the refined time resolution at which these tracks are tested by the WL 20 system.

d’Antona & Mazzitelli (1998), can be up to a factor of two too old, relative to accreting PMS models, making the true ages of WL 20:E and WL 20:W as young as $1–1.3 \times 10^6$ yr, consistent with the oldest plausible Class I source age of $1.6 \times 10^6$ yr for WL 20:S. The errors in the masses of PMS objects derived from non-accreting vs. accreting tracks are much smaller, being negligible in the case of WL 20:E and at the 10% level for WL 20:W (found by placing these sources on Figure 13 of Tout et al. 1999).

4.3. The Nature of WL 20:S

In this work, we have found that: 1) WL 20:S is the reddest and most luminous member of the WL 20 system; 2) it is highly variable on timescales of a few years; 3) it contains most of the dust in the system in a mid-IR emitting region some 40 AU in diameter; and 4) that it is the source of the observed centimeter emission.

The most likely explanation for the mid-IR appearance of WL 20:S is that it is experiencing a phase of enhanced (and varying) accretion activity, perhaps due to interactions with its neighbors. This is especially likely in view of the fact that the SED of WL 20:S is consistent with the presence of a flared disk of $\sim 250$ AU in radius (Chiang & Goldreich 1999, Eqn. 1), very similar to the projected separation of 280 AU between WL 20:S and WL 20:W. We observe a structure whose 40 AU diameter size appears to be wavelength-independent in the mid-IR: this structure may be the flared disk surface. The IRAS fluxes for the WL 20 system, as a whole, are systematically larger than the sum of the fluxes of the individual components derived from ground-based observations (see Table 2). This discrepancy in the measured fluxes in different-sized beams implies the presence of material on scales larger than those to which the ground-based observations are sensitive, but that still fall within an IRAS beam. Thus, $\geq 40\%$ of the observed IRAS fluxes are emitted from regions $10^{16}–120^\prime$ in size, corresponding to the size scales of infalling envelopes. It may very well be that WL 20:S is actively accreting matter from the envelope, through its flaring disk, while its companions have already ceased significant accretion.

If this is true, it addresses one of the primary objections to WL 20 being a true triple system, as opposed to a chance superposition of a binary (WL 20:E & W) with a single source (WL 20:S). If WL 20 is a triple with an age of $\sim 2 \times 10^6$ yr, that is still uncomfortably old to have the presence of a Class I source, which would normally be presumed to be $< 1 \times 10^6$ yr old. This would appear to argue that WL 20:S is more likely a chance superposition. However, if accretion has been continued to a late phase due to tidal interactions with the other members, then the shape of the SED of an individual source within a binary/multiple system is an indicator only of the accretion activity of that source, and has little to do with its age.

Preliminary studies of accretion in triple systems have so far focussed on hierarchical triples, in which the separation between two sources is much smaller than their distance to the third component, a circumstance clearly not applicable to the WL 20 system. In fact, if formation proceeds through fragmentation, then the resultant triples are typically not in a very hierarchical configuration. The stability of accreting triples has been examined by Smith
et al. (1997). In general, if the maximum separation of the closer pair (280 AU projected separation for WL 20:S & WL 20:W) is comparable to the minimum separation of this pair to the third component (400 AU projected separation from WL 20:W to WL 20:E), then the stability of the system is questionable. From the above analysis of existing PMS models, the current best mass determinations for this system are 0.62–0.68 $M_\odot$ for WL 20:E and 0.51–0.55 $M_\odot$ for WL 20:W, respectively, and $\sim 1.0$ $M_\odot$ for WL 20:S from the constraints given by its 1.0–1.8 $L_\odot$ luminosity. According to the criterion for stability of triple systems given by Harrington (1977), as quoted in Smith et al. (1997), the WL 20 system should be dynamically unstable. The behavior of dynamically unstable accreting triple systems has not yet been examined. It may be that some fraction of single stars are formed from the disintegration of unstable triple systems.

5. Conclusions

We have presented sub-arcsecond, mid-infrared imaging photometry of the WL 20 triple system at 7.9, 10.3, 12.5, 17.9, 20.8, and 24.5 $\mu$m. When supplemented by spatially-resolved, near-infrared imaging photometry from ProtoCAM at the IRTF, these combined data allow solid determinations of the spectral energy distribution of each source individually, as well as accurate luminosity determinations. We find the source luminosities for WL 20:E, WL 20:W, and WL 20:S to be 0.61 $L_\odot$, 0.39 $L_\odot$, and 1.0–1.8 $L_\odot$, respectively. For WL 20:E and WL 20:W, 0.53 $L_\odot$ and 0.35 $L_\odot$ can be attributed to photospheric emission alone.

WL 20 can now be classified as an “infrared companion system,” with WL 20:S exhibiting an embedded protostellar (Class I) SED, while its two neighbors, WL 20:E and WL 20:W, each exhibit T Tauri star (Class II) SEDs. The infrared companion, WL 20:S, is the dominant luminosity source in the system. WL 20:S differs from its T Tauri companions in three important respects: 1) its near- and mid-IR fluxes vary significantly over timescales of years; 2) it is well-resolved at mid-IR wavelengths, with a constant, wavelength-independent source diameter of 40 AU; and 3) it is found to be the source of the radio cm emission in the system.

Since the effective temperatures of WL 20:E & W are known from spatially-resolved near-IR spectroscopy, we can place these sources on a Hertzsprung-Russell diagram. We are thus able to test currently available pre-main-sequence evolutionary tracks at unprecedentedly high temporal resolution and find that of the non-accreting models, the d’Antona & Mazzitelli (1998) tracks yield the most plausible system age, at 2.0–2.5 x 10$^6$ yr. The inferred source masses from these tracks at these ages are 0.62–0.68 $M_\odot$ for WL 20:E and 0.51–0.55 $M_\odot$ for WL 20:W, respectively.

We cannot, at present, independently determine a mass or age for the infrared companion, WL 20:S. However, the intriguing possibility now exists of determining the spectral type, and, therefore, the effective temperature of this embedded source with the new generation of high-resolution spectrographs on 8–10 m ground-based telescopes. Once an effective temperature determination has been made spectroscopically, and assuming system coevality, one could locate WL 20:S on an isomass track, independently of its known luminosity. Thus, the possibility exists, for the first time, to directly derive the accretion luminosity of a Class I protostar.

Millimeter interferometry of this unique triple system would advance our understanding of the gas dynamics involved, processes which cannot be explored in any other way. Higher temporal resolution spatially-resolved imaging and monitoring of WL 20 at infrared wavelengths, combined with detailed modeling of its appearance will also lead to a more detailed understanding of the actual accretion processes taking place in WL 20:S.

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