51 ERIERIDANI AND GJ 3305: A 10–15 Myr OLD BINARY STAR SYSTEM AT 30 PARSECS

E. D. FEIGELSON, W. A. LAWSON, M. STARK, L. TOWNSLEY, AND G. P. GARMIRE

Received 2005 September 10; accepted 2005 November 17

ABSTRACT

Following the suggestion of Zuckerman and coworkers, we consider the evidence that 51 Eri (spectral type F0) and GJ 3305 (M0), historically classified as unrelated main-sequence stars in the solar neighborhood, are instead a wide physical binary system and members of the young β Pic moving group (BPMG). The BPMG is the nearest (d ≲ 50 pc) of several groups of young stars with ages around 10 Myr that are kinematically convergent with the Oph-Sco-Cen association (OSCA), the nearest OB star association. Combining South African Astronomical Observatory optical photometry, Hobby-Eberly Telescope high-resolution spectroscopy, Chandra X-Ray Observatory data, and Second US Naval Observatory CCD Astrograph Catalog kinematics, we confirm with high confidence that the system is indeed extremely young. GJ 3305 itself exhibits very strong magnetic activity but has rapidly depleted most of its lithium. The 51 Eri/GJ 3305 system is the westernmost known member of the OSCA, lying 110 pc from the main subgroups. The system is similar to the BPMG wide binary HD 172555/CD –64 1208 and the HD 104237 quintet, suggesting that dynamically fragile multiple systems can survive the turbulent environments of their natal giant molecular cloud complexes, while still having high dispersion velocities imparted. Nearby young systems such as these are excellent targets for evolved circumstellar disk and planetary studies, having stellar ages comparable to that of the late phases of planet formation.

Key words: binaries: visual — open clusters and associations: individual (Ophiuchus-Scorpius-Centaurus) — planetary systems: formation — stars: individual (51 Eridani, GJ 3305) — stars: pre-main sequence — X-rays: stars

1. INTRODUCTION

1.1. Young Stars Near Earth Are Mostly OSCA Outliers

Observations revealing the transition from gaseous circumstellar disks to protoplanetary systems are limited not by the capabilities of telescopes but by the available samples of nearby young stars. Pre-main-sequence (PMS) evolutionary models indicate that a 10 Myr old protoplanet with mass ≳ 10M_J should exhibit I ≲ 20 at a distance of 30 pc (Baraffe et al. 2002). The principal difficulties in finding stars with dissipating disks or protoplanets are that no active star-forming regions lie within ≲ 150 pc and that older PMS stars drift far from their natal clouds, where they are difficult to distinguish from the Galactic field population.

Most known nearby older PMS stars are kinematically linked to the populous Ophiuchus-Scorpius-Centaurus association (OSCA) of PMS stars, with its main concentrations at mean distances of 118–145 pc (Blauw 1991; de Zeeuw et al. 1999). Ages range from 17 Myr in the Lower Centaurus-Crux (LCC) subgroup (Mamajek et al. 2002) to < 1 Myr in the Ophiuchus cluster, where stars are still forming today. Several sparse populations distributed over the southern sky are kinematically convergent with the rapidly moving OSCA and exhibit circumstellar disks, lithium excesses, or other indicators of stellar youth. These include the TW Hya association (TWA), β Pic moving group (BPMG), η Cha cluster, ε Cha group, and several “isolated” Herbig Ae/Be stars with low-mass companions. Their positions in the sky are shown in Figure 1 (a similar figure with proper motion vectors and references appears in Feigelson et al. 2003). These stars are distributed over a large region around the rich OSCA concentrations, likely propelled by supersonic motions of gaseous eddies in the OSCA’s turbulent giant molecular cloud (Feigelson 1996). It is quite likely that other stellar systems also lie away from the main OSCA subgroups. The BPMG in particular has members very close to the Sun. The circumstellar disk of its most massive member, β Pic (d ≲ 10 pc), has been subject to very intensive study (Lagrange et al. 2000), and a disk has recently been reported around the BPMG member AU Mic (d = 10 pc; Kalas et al. 2004).

We discuss here two stars proposed by Zuckerman et al. (2001a) to be both a physical binary and nearby members of the ∼12 Myr old BPMG: the V = 5.2 F0 star 51 Eri and the V = 10.6 M0.5 star GJ 3305, separated by 66″. This suggestion is in conflict with previous studies of these stars that have considered them to be unrelated main-sequence stars at d = 31 pc and d = 15 pc, respectively (§ 1.2). We present new X-ray and optical observations (§ 2) and consider in detail the kinematic, spectroscopic, photometric, and magnetic activity properties of these stars (§ 3). We conclude that they indeed are outlying members of the OSCA. Thus, 51 Eri and GJ 3305 are among the nearest 10–15 Myr old stars and represent one of the best nearby young stellar systems for study of planet formation. Their protoplanetary disks have largely dissipated, and protoplanets might be detectable.

1.2. The Misclassification of GJ 3305

The literature on 51 Eri and nearby associated stars has been confused. Figure 2 (top) shows the neighborhood from the 2MASS J-band survey, and Table 1 lists the labeled stars. Many of these stars are missing from star catalogs due to saturation and diffracted light from the V = 5.2 51 Eri, especially those based on all-sky Schmidt telescope photographic surveys; 51 Eri itself
has a *Hipparcos* parallax measurement that, when combined with photometry and spectroscopy, confirms that it is an F0 star positioned on, or very near, the main sequence at a distance of 29.8 ± 0.8 pc (for convenience, we call this 30 pc throughout this paper). From Burnham’s report in 1916, it was considered a double star with star 7 as its companion. But this is incorrect: kinematic measurements from the recent Second US Naval Observatory CCD Astrograph Catalog (UCAC2) survey (Table 1) established that star 7 does not share the proper motions of 51 Eri and must be an unrelated star.

GJ 3305 has been classified, incorrectly in our view, as a disk dwarf with a photometric distance of ≈15 pc based on the assumption that the star resides on the main sequence. Propagation of this assumption has lead to the inclusion of GJ 3305 in other catalogs and surveys of nearby stars, e.g., the Nearby Stars catalog of Gliese & Jahreiss and the Palomar/Michigan State University nearby star spectroscopic survey of Gizis et al. (2002). GJ 3305 is cataloged as a chromospherically active flare star, presumably on account of its Hα emission, and more recently because of the detection of strong X-ray variability by Fuhrmeister & Schmitt (2003). Their calculation of the total energy released during an X-ray flare detected during the *Röntgensatellit (ROSAT)* All-Sky Survey of 3.4 × 10³⁴ ergs is derived assuming a distance of 15.2 pc, with this value rising by a factor ≈4 if GJ 3305 instead resides at 30 pc as we argue in this paper. Across the characteristic timescale of the flare (we adopt 0.2 days) the luminosity of the flare was $L_X \approx 8 \times 10^{30}$ ergs s⁻¹. For a spectral type of M0.5 and $V = 10.6$ for GJ 3305 at 30 pc, and adopting the dwarf temperature and bolometric correction sequences of Kenyon & Hartmann (1995), as is appropriate for “older” PMS stars (Mamajek et al. 2002; Lyo et al. 2004), we derive a stellar luminosity $L_{bol} = 0.14 L_\odot$ and find the ratio of X-ray flux to bolometric flux to be

$$\log \frac{L_X}{L_{bol}} \approx -1.8$$

during the flare. Our *Chandra* observation indicates a lower quiescent level for GJ 3305 of $\log \frac{L_X}{L_{bol}} \approx -3.5$, a value similar to the “saturation” level of $\log \frac{L_X}{L_{bol}} \sim -3$ observed for magnetically active late-type PMS stars.

### 2. OBSERVATIONS

#### 2.1. Chandra X-Ray Observatory

A 16′ × 16′ region around 51 Eri was observed for 3.15 ks with the Advanced CCD Imaging Spectrometer (ACIS) on board the *Chandra X-Ray Observatory*. The instrument and detector are described by Weisskopf et al. (2002). This snapshot observation took place on 2003 November 20. Data analysis followed procedures described in Townsley et al. (2000, 2003) and Getman et al. (2005) using the IDL- and CIAO-based script *acis_extract* package. One processing step, the removal of 0.075 randomization in event location, was omitted due to the short exposure time. Figure 2 (bottom) shows the central 6′ × 6′ of the resulting ACIS image after correction for charge transfer inefficiency and data selection steps. A spatial offset of 0.′7 was applied to align the sources associated with 51 Eri and GJ 3305 to the *Hipparcos* reference frame.

Thirty-one candidate X-ray sources were located using a wavelet-based detection algorithm (Freeman et al. 2002). Events for each source were extracted using *acis_extract*. Here, events were extracted in a small region around each source containing 95% of the enclosed energy derived from the point-spread function of the telescope at that position, and a local background was defined from a nearby source-free region. The extraction of GJ 3305 required a special annular region because the central pixels were subject to photon pileup, a saturation of the detector occurring when more than one photon arrives in a pixel during the 3.2 s between CCD readouts. We extracted 30% of the incident photons arriving between the 60% and 90% enclosed

---

5 *VizieR Online Data Catalog, 1289 (N. Zacharias et al., 2003).*

6 *GJ 3305 does not appear in their published catalog but was added by the SIMBAD staff as an NN (new neighbor) addition to the GJ catalog.*

7 *Description and code for acis_extract are available at http://www.astro.psu.edu/xray/docs/TARA/ac_users_guide.html.*
sources. The positions have a precision of ±0.2. Extracted counts are the number of extracted counts in the total 0.5–8.0 keV Chandra band, while soft counts are the subset of counts in the 0.5–2.0 keV band. Spectral analysis of 51 Eri and GJ 3305 is based on optically thin plasma models with solar elemental abundances, where the plasma energies $kT$ are obtained by a least-squares fit of the photon energy distribution using the XSPEC software package (Arnaud 1996). No interstellar absorption is seen in the spectra. The spectrum and best-fit model for GJ 3305 are shown in Figure 3. It requires a two-temperature plasma, which is common in ACIS spectra of magnetically active late-type stars. Fluxes are found by integrating the best-fit spectrum over the 0.5–8 keV band, and luminosities are calculated assuming the Hipparcos distance to 51 Eri of 30 pc.

2.2. Hobby-Eberly Telescope Spectroscopy

High-resolution spectra of 51 Eri and GJ 3305 were taken on three sequential nights, 2003 December 13–15 with the High Resolution Spectrograph (HRS; Tull 1998) on the 9.2 m Hobby-Eberly Telescope (HET; Ramsey et al. 1998). The HRS uses an echelle mosaic with cross-dispersing gratings imaging onto a mosaic of two thinned 2K × 4K CCD detectors with 15 μm pixels. The instrument lies in a stationary, climate-controlled room and is fiber-coupled to the primary focus of the telescope. The chosen 600 groove mm$^{-1}$ grating with 20° fibers gives resolving power $R = 60,000$ over the interval ~5300–7250 Å. We obtained one 30 s exposure of 51 Eri and two 900 s exposures of GJ 3305 each night, along with instrument calibration exposures.

The spectra were processed, extracted, and wavelength-calibrated with standard IRAF routines. A difficulty arose because the instrument continuum calibration lamp for flat-fielding sometimes exhibits Li i λ6708 and Na D emission lines with 18% and 12% amplitude, respectively, that coincide with stellar lines of interest. We replaced 2 Å around each of these lines with a linear interpolation of the surrounding flat-lamp spectrum; ≈2% systematic residual structure is expected from this procedure. For the GJ 3305 spectra, background spectra from two fibers pointed at blank sky were subtracted, and cosmic rays were rejected. These steps were unnecessary for 51 Eri owing to the brightness and brevity of the exposures. Spectra from the three nights were combined, and the continua of the wavelength-calibrated star spectra were removed. No radial velocity correction or calibration was made. No night-to-night variation in any spectral feature was seen.

Figure 4 shows the resulting spectra around the Na D, Hα, and Li i λ6708 lines. The signal-to-noise ratio at Hα and Li i λ6708 is S/N = 230:1 for GJ 3305 and 180:1 for 51 Eri. The strength of the lithium absorption line in GJ 3305 is of greatest interest in our discussion below. Figure 4 (bottom) shows the spectra with a relatively low global continuum fit that gives a Li i λ6708 equivalent width $EW = 0.09$ Å. A continuum fit that passes near the peaks of local fluctuations, which takes into account our high S/N and the likely presence of uncataloged absorption lines, gives $EW = 0.14$ Å. (Jeffries et al. [2003] discuss the sensitivities of reported lithium line strengths to the choice of continuum levels.) A faint absorption line with $EW = 0.03$ Å appears in the 51 Eri spectrum; we believe this is the residual from the interpolated continuum lamp calibration. The true GJ 3305 line strength may thus be 0.03 Å lower than measured here. Altogether, we adopt $EW = 0.12 ± 0.03$ for the Li i λ6708 line of GJ 3305.

The weak Hα profile of GJ 3305 with roughly 1 Å EW and little variability over three nights of observation is commensurate with GJ 3305 being a weakly active, nonaccreting PMS star. It has a spectroscopic analog in the several-megayears-younger star RECX 10 in the η Cha cluster, with a spectral type of M0.3

Most of these sources are extragalactic. Five were detected in a ROSAT pointed observation (WGACAT 0437.2−0210, 0437.3−0222, 0437.5−0236, 0437.6−0231, and 0437.8−0230) but have not been studied. Four have $R ≃ 19$–20 counterparts on the Digitized Sky Survey, and one is associated with the $V ≃ 14.5$ S0 galaxy UGC 03105 at redshift $z = 0.03$. The remaining optical counterparts are too faint to appear in all-sky surveys. These sources are typical of the extragalactic population seen in Chandra images, which often are active galactic nuclei with $0.1 < z < 1$ (Brandt & Hasinger 2005).

Table 2 provides detailed results for the two stars of interest here. CXOU is the official designation of the Chandra X-ray

energy circles, and adjusted the effective area (CIAO’s auxiliary response function file) accordingly.

Most of these sources are extragalactic. Five were detected in a ROSAT pointed observation (WGACAT 0437.2−0210, 0437.3−0222, 0437.5−0236, 0437.6−0231, and 0437.8−0230) but have not been studied. Four have $R ≃ 19$–20 counterparts on the Digitized Sky Survey, and one is associated with the $V ≃ 14.5$ S0 galaxy UGC 03105 at redshift $z = 0.03$. The remaining optical counterparts are too faint to appear in all-sky surveys. These sources are typical of the extragalactic population seen in Chandra images, which often are active galactic nuclei with $0.1 < z < 1$ (Brandt & Hasinger 2005).

Table 2 provides detailed results for the two stars of interest here. CXOU is the official designation of the Chandra X-ray
TABLE 1
STARS IN THE VICINITY OF 51 ERI

| Number | R.A.  | Decl. | UCAC Number | Other Catalogs | UC | J   | \( \mu_a \) | \( \mu_b \) |
|--------|-------|-------|-------------|----------------|----|-----|---------|---------|
| 1........| 28 00 | 29 31 | 30947507    | CMC, USNO       | 15.0| 13.5| 12.3 ± 7.5 | -6.8 ± 7.5|
| 2........| 29 36 | 26 04 | 30947509    | GSC             | 14.3| 13.3| 5.3 ± 5.4 | -10.6 ± 5.4|
| 3........| 33 30 | 30 36 | 30794265    | CMC, USNO       | 14.1| 13.1| 5.6 ± 7.6 | -5.2 ± 7.6|
| 4........| 33 48 | 28 39 | 30947515    | APM             | 15.5| 14.6| 7.4 ± 7.5 | -1.4 ± 7.4|
| 5........| 36 06 | 28 25 | ...         | 51 Eri, SD, WDS, CCDM, ... | 5.2 | 4.7 | 43.3 ± 0.8 | -64.3 ± 0.6|
| 6........| 37 30 | 29 28 | 30947521    | CMC, GJ, StKM, RBS, ... | 10.0| 7.3 | 46.1 ± 2.8 | -64.8 ± 3.0|
| 7........| 38 00 | 28 16 | 30947523    | WDS, CCDM, HIC  | 11.8| 11.3| 0.6 ± 1.4 | 20.2 ± 1.4|
| 8........| 43 18 | 28 25 | 30947531    | CMC             | 14.2| 13.3| 12.9 ± 7.5 | -3.2 ± 7.6|
| 9........| 43 24 | 29 11 | 30947532    | CMC             | 15.9| 14.4| 6.3 ± 7.5 | -2.8 ± 7.5|
| 10........| 45 36 | 30 26 | 30794283    | ...             | 14.6| 13.6| -5.9 ± 7.5 | -9.5 ± 7.5|
| 11........| 45 54 | 28 22 | 30947535    | CMC, GSC, SD, Tycho, ... | 10.9| 10.3| 7.8 ± 2.9 | -6.0 ± 3.3|
| 12........| 47 24 | 30 57 | 30794286    | ...             | 13.1| 12.1| -4.8 ± 7.5 | -8.7 ± 7.5|

Notes.—Col. (1): Running star number from Fig. 2 (top). Cols. (2)–(3): Right ascension and declination, J2000.0. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (4): UCAC2 star number (VizieR Online Data Catalog, 1289 [N. Zacharias et al., 2003]). Col. (5): APM = Automated Plate Measurement catalog APMCAT-POSS1-1.0 (Irwin & McMahon 1992); Tycho = Tycho 2 catalog (Høg et al. 2000); USNO = USNO B1.0 catalog (Monet et al. 2003); WDS = Washington Visual Double Star Catalog (ver. 2.2) from the Palomar Schmidt telescope; RBS = ROSAT 2002; GJ = Catalog of Nearby Stars, preliminary third version (VizieR Online Data Catalog, 5070 [W. Gliese & H. Jahreiss, 1995]); GSC = Guide Star Catalog (VizieR Online Data Catalog, 1274 [J. Dommanget & O. Nys, 2002]); CMC = Carlsberg Meridian Telescope CCD Drift Scan Survey (ver. 1.0) catalog (Evans et al. 2001a; see their Table 2) gives an average lithium EW = 0.26 Å. GJ 3305 has the lowest EW by a factor of ≈2 compared to the other three stars, and thus signals that depletion has been unusually efficient in this star. This average EW for BPMG candidate members compares to average values of ≈0.5 Å for late-type members of both the ~10 Myr old TWA (Webb et al. 1999) and η Cha star cluster (Mamajek et al. 1999).

2.3. South African Astronomical Observatory Photometry

We have obtained a tentative measure of the rotation period of GJ 3305 by searching for optical photometric variations that are determined from precise spectrophotometric study (Lyo et al. 2004). Both stars have weak, narrow Hα profiles of 1 Å EW and velocity width (measured at the 10% height of the emission-line profile above the surrounding continuum) \( v_\text{10} = 110 \text{ km s}^{-1} \), indicative of a line of chromospheric origin with no evidence for wing-broadening that might indicate ongoing low levels of disk accretion (Lawson et al. 2004). At echelle resolution, the Hα profiles of both stars show weak self-absorption signatures.

In the spectral regions of interest here, the principal difference between GJ 3305 and RECX 10 is the strength of the Li i /6708 line; EW = 0.12 Å for GJ 3305 (see the discussion above) and EW = 0.6 Å for RECX 10 (measured from unpublished echelle spectra; Mamajek et al. 1999) had earlier obtained a similar result of EW = 0.5 Å from medium-resolution spectra). Our measurement of low lithium EW in GJ 3305 reinforces the evidence that significant lithium depletion can be present in ~10–15 Myr stars (§ 6). Zuckerman et al. (2001a) used lithium measurements as evidence that the BPMG has an age intermediate between that of the TWA (~10 Myr) and Tucana-Horologium (~30 Myr) group stars. Adding our lithium measurement for GJ 3305 to those for three late-type BPMG candidate members with spectral types ranging from K0 to M1 measured by Zuckerman et al.

TABLE 2
X-RAY PROPERTIES OF 51 ERI AND GJ 3305

| Property | 51 Eri | GJ 3305 |
|----------|--------|--------|
| CXOU     | 043736.12-022824.7 | 043737.46-022928.3 |
| R.A.      | 04 37 36.12 | 04 37 37.46 |
| Decl.     | -02 28 24.7 | -02 29 28.3 |
| Extracted counts | 41 | 222 |
| Soft counts | 41 | 182 |
| 0.7 keV   | 0.2 | 0.6, 2.8 |
| Flux ergs s\(^{-1}\) cm\(^{-2}\) | \(1.3 \times 10^{-13}\) | \(1.6 \times 10^{-12}\) |
| Luminosity ergs s\(^{-1}\) cm\(^{-2}\) | \(1.4 \times 10^{28}\) | \(1.7 \times 10^{29}\) |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
modulated by the periodic rotation of starspots. A series of observations was made in the $BVRI$ photometric bands over six consecutive nights, 2004 December 8–13, with the 1 m telescope and a 1K × 1K CCD detector at the South African Astronomical Observatory (SAAO). Four sets of observations were obtained on most nights, to reduce the 1 day aliasing effects that can result from observations being made at a single observing site. The observations and analysis of the photometry follow that described by Lawson et al. (2001). In summary, differential measurements of the suspected variable star are produced by comparison with other stars in the CCD field that are assumed to be constant, and the resulting differential light curve is then subjected to Fourier analysis. Unfortunately, GJ 3305 resides in a sparse field toward the Galactic anticenter [$l, b = (199°, -31°)$], resulting in few usable comparison stars within a radius of several arcminutes. With exposure times optimized for GJ 3305, only in the $B$ band were there nearby field stars of comparable brightness to GJ 3305; in the other bands the usable comparison stars were a few magnitudes fainter than GJ 3305, resulting in unacceptable noise in the differential observations. We therefore describe only the analysis of our $B$-band observations here.

The $B$-band light curve shows variations of low amplitude over the duration of the observations. Fourier analysis of the light curve recovered a periodicity at $f = 0.164$ days$^{-1}$, or $P = 6.1$ days (Fig. 5). The recovered period is comparable to the length of the observing run, and so we treat the result with caution, but the

![Graphs showing photometry data for GJ 3305 and 51 Eri in different bands.](image-url)
data when phased to a period of ≈6 days have less scatter than when they are phased to substantially different periods. We therefore tentatively adopt a period of $P = 6.0 \pm 0.5$ days for GJ 3305 and await the acquisition of photometry obtained across a longer timeline to confirm and improve this result. In Figure 5a we show our $B$-band photometry phased on a periodicity of $f = 0.164$ days$^{-1}$. In Figure 5b we show the amplitude spectra of the photometry (thick line) and that following prewhitening of the data set with the identified periodicity (thin line), across a frequency range of 0–2 days$^{-1}$. The collapse of the $f = 0.164$ day$^{-1}$ periodicity and its associated $(1 - f)$ day$^{-1}$ and $(1 + f)$ day$^{-1}$ aliases in the prewhitened spectrum suggests that the period of GJ 3305 is not far removed from $P = 6$ days. For a sine wave amplitude of 0.015 mag, and adopting a noise level of 0.003 mag over the 0–2 day$^{-1}$ frequency interval, the periodicity has a S/N of 5. At higher frequencies both the original and prewhitened spectra show noise at a level of ≈0.05 mag, indicating that the variations seen within an individual night of data are the result of random photometric noise and not due to the presence of high-frequency periodicities.

3. EVOLUTIONARY STATUS OF 51 ERI AND GJ 3305

In this section we reevaluate the evolutionary state of these two stars based on various lines of argument. It is worthwhile to recall that it is very difficult to determine the age of isolated AF-type stars on or near the main sequence from their spectral and photometric properties due to the convergence of isochrones in the H–R diagram. We note especially the extended debate concerning the age of the A3 star $\beta$ Pic. Once considered to be a post-main-sequence star with age $t \approx 200$ Myr or a main-sequence star with age $t \approx 100$ Myr, its kinematical association with PMS stars and the OSCA strongly argue for an age around 10–15 Myr (Barrado y Navascués et al. 1999; Mamajek & Feigelson 2001; Zuckerman et al. 2001a; Ortega et al. 2002, 2004). We synthesize several lines of evidence that together strongly argue that 51 Eri and GJ 3305 are also OSCA outliers with ages 10–15 Myr.

3.1. Astrometry and Kinematics

The UCAC2 proper motion of GJ 3305 ($\mu_\alpha$, $\mu_\delta$) = (46.1, $-64.8$) mas yr$^{-1}$ is nearly identical to the proper motion of ($\mu_\alpha$, $\mu_\delta$) = (43.3, $-64.3$) mas yr$^{-1}$ found by Hipparcos for 51 Eri itself. None of the other ≈6000 UCAC2 stars within an area...
of 10 deg² centered on the position of 51 Eri have a proper motion within 10 mas yr⁻¹ of that of 51 Eri. We have already established that the 51 Eri motion is convergent with the OSCA 10–15 Myr ago; see Figure 1. The radial velocity of 51 Eri is 21 ± 2 km s⁻¹ (Kharchenko et al. 2004). Although we did not calibrate our HET spectra against radial velocity standards, differential velocity measurements of spectral features in 51 Eri and GJ 3305 suggest that both stars share the same radial velocity to within 2 km s⁻¹.

3.2. Magnetic Activity

GJ 3305 has an X-ray-to-bolometric-luminosity ratio \( \log L_X/L_{bol} = -3.5 \), which is near the saturation level of \( \log L_X/L_{bol} \sim -3 \) for late-type magnetically active PMS stars. This is far above the range of \( \log L_X/L_{bol} = -5.2 \pm 0.5 \) seen in old-disk, early M-type stars (Fleming et al. 1995). A faint X-ray source with \( L_X = 1.4 \times 10^{28} \) ergs s⁻¹ and a soft spectrum coincides with the F0 primary, 51 Eri. At 30 pc distance, this yields a low value of \( \log L_X/L_{bol} = -6.2 \), as is expected from the quiescent coronal gas in the atmosphere of an F0 star.

This high level of X-ray emission is a strong indicator for stellar youth. We compare \( \log L_X/L_{bol} \) of GJ 3305 with stars in other young stellar clusters and associations in Figure 6 (top). Due to mass dependencies in PMS X-ray emission (Preibisch et al. 2005), we limit the comparison to stars in a limited spectral range. The saturated X-ray level implies an age \( \lesssim 100 \) Myr.

3.3. H-R Diagram

In Figure 7 we compare the location of 51 Eri and GJ 3305 in the H-R diagram to the predictions of the PMS evolutionary tracks of Siess et al. (2000). The error bars indicate the effect of a nominal 0.5 subtype uncertainty in the spectral types of the two stars; F0 for 51 Eri and M0.5 for GJ 3305. The resulting range in the stellar luminosities caused by the adoption of the 0.5 subtype uncertainty is encompassed by the plotted size of the points in Figure 7. It is possible that 51 Eri may lie slightly elevated above the zero-age main sequence (ZAMS) of Siess et al. (2000), although only marginally so owing to the adopted uncertainty and the coarseness of the grid in the temperature range appropriate for F-type stars. At 30 pc distance, GJ 3305 is clearly PMS with an inferred age of \( 13^{+4}_{-1} \) Myr, consistent with the age estimate of \( 12^{+8}_{-3} \) Myr given for the BPGM by Zuckerman et al. (2001a) and the 17 Myr age given for the rich LCC OSCA subgroup by Mamajek et al. (2002). From comparison with the models of Siess et al. (2000) we obtain \( M = 1.6 M_\odot \) for 51 Eri and \( M = 0.5 M_\odot \) for GJ 3305.

3.4. Multiplicity and Dynamical State

If we assume that the physical separation of 51 Eri and GJ 3305 is close to the projected separation of 66″, or \( \approx 2000 \) AU at \( d = 30 \) pc, and that the orbit is circular, then the binary orbital period is \( \approx 60,000 \) yr and the orbital velocity of GJ 3305 is \( \approx 0.7 \) km s⁻¹. This represents a very fragile system; any dynamical perturbation of order 1 km s⁻¹ during the last 10–15 Myr would have been sufficient to disrupt the binary, yet the binary system has completed \( \approx 200 \) orbital periods. This is reminiscent of a similar multiple system: the four low-mass PMS stars with 500–1500 AU orbits around the 3–5 Myr intermediate-mass Herbig Ae star HD 104237, which is also kinematically linked to the OSCA (Feigelson et al. 2003). Systems such as 51 Eri and HD104237 must have originated in a dynamically quiescent star formation environment. Dynamical simulations of stellar clusters by Kroupa (1998) indicate that wide binaries with total mass around \( 2 M_\odot \) and mass ratio around 3:1, as in 51 Eri/GJ 3305, can survive if the initial star density is not too high.

3.5. Rotational Velocities

The \( v \sin i \) projected rotational velocity of 51 Eri was measured to be \( 71.8 \pm 3.6 \) km s⁻¹ by Reiners & Schmitt (2003), with
indications from suspected asymmetries and variations in the line profiles that the star was spotted. Koen & Eyre (2002) list 51 Eri as a candidate Hipparcos variable star with a period determined by Fourier analysis of the Hipparcos photometry of \( P = 0.65 \) days and a fitted sine-wave amplitude of 0.005 mag. For an F0 dwarf on or near the main sequence with characteristic mass and radius of \( M \approx 1.5 M_\odot \) and \( R \approx 1.5 R_\odot \), the \( v \sin i \) velocity and proposed period of the star can be reconciled if 51 Eri is being observed at a moderate inclination angle of \( i \approx 45^\circ \).

There is no literature value for the projected rotational velocity for GJ 3305; however, our HET spectra for GJ 3305 show line profiles for absorption lines near \( H_\alpha \) of width exceeding the expected instrumental broadening due to the HRS. From the measured FWHM of the profiles we estimate the contribution from all sources of line broadening to be \( v \approx 10 \) km s\(^{-1}\). Thus, \( v \sin i < 10 \) km s\(^{-1}\), and for a young, \( R \approx 0.7 R_\odot \), early-M star the inferred rotation period is \( P > 4 \sin i \) days, consistent with our tentative measured rotation period of \( P = 6.1 \) days; see §2.3. We have not attempted a line profile deconvolution that would allow us to accurately determine the projected rotational velocity for the star.

4. ORIGIN OF THE 51 ERI AND GJ 3305 SYSTEM

There is little doubt that 51 Eri and its companion constitute a physical binary. Not one of several thousand UCAC2 stars in the immediate vicinity share the unusually large proper motions seen in these two stars.

We conclude that both the 1.6 \( M_\odot \) 51 Eri and its X-ray-selected, 0.5 \( M_\odot \) companion are \( \approx 10 \) Myr outlying members of the OSCA. They are now seen at an angular distance of \( \approx 100^\circ \), and a physical distance of \( \approx 110 \) pc, from the center of the nearest (LCC) rich concentration of OSCA stars. This implies that the 51 Eri system was formed from molecular gas with a velocity vector displaced \( \approx 9 \) km s\(^{-1}\) from that of the rich OSCA concentrations. This is consistent with dispersions seen over large scales in giant molecular cloud complexes that are attributed to turbulence (Feigelson 1996).

OSCA outliers include a number of PMS stars with rapid gas accretion from infrared-bright (IRAS-detected) circumstellar disks. These include TW Hya and Hen 3-600A in the Taurus CHA (Muzerolle et al. 2000), ECHAJ 0843.3–7905 and RECX 11 in the \( \eta \) Cha cluster (Lawson et al. 2004), and the several Herbig Ae/Be stars noted in Figure 1. The source \( \beta \) Pic has a prominent reflection disk and is accreting cometary-sized bodies (Lagrange et al. 2000). In contrast, both 51 Eri and GJ 3305 appear to lack prominent disks. Also, 51 Eri displays a \((V-K)\) color of 0.68, consistent with its F0 spectral type. However, the star may have a small \((K-[12])\) excess of \( 0.2 \) \pm 0.1 when compared to dwarf colors ascribed by Kenyon & Hartmann (1995), which may indicate the presence of a weak disk. GJ 3305 has 2MASS \( JHK \) colors consistent with its listed spectral type of M0.5; however, it has \((V-[2MASS])\) colors closer to that of an M2 dwarf, which may indicate the presence of a weak disk or a minor misclassification of its spectral type. We note that GJ 3305 has no known late-M companion; McCarthy & Zuckerman (2004) included GJ 3305 in an unsuccessful search to detect brown dwarfs orbiting at \( a = 75-300 \) AU around a hundred nearby G-, K-, and M-type stars.

Sensitive near-infrared coronographic imagery and far-infrared photometry with the Spitzer Space Telescope may detect faint, evolved disks around one or both stars. Perhaps most exciting is the possibility that, with disks that have largely dissipated, protoplanets might be present among these stars. For example, making use of the substellar models of Baraffe et al. (2002), a \( 5M_\oplus \) planet in a circular face-on orbit with \( a = 30 \) AU should appear as a \( K = 15.4 \) source at a separation of \( 1'' \) from the star. For such a planet surviving GJ 3305, \( \Delta K = 9 \) mag; this is a demanding but not insurmountable challenge using existing technologies.

5. HD 172555/CD − 64 1208 AND OTHER SIMILAR WIDE BINARY SYSTEMS

While it may seem at first unlikely that a weakly bound binary can survive the turbulent environment of the OSCA giant molecular cloud, a considerable fraction of the identified BPMG members are similar. Visual multiple systems in the list of Zuckerman et al. (2001a) include 51 Eri/GJ 3305 (F0+M0.5 with projected separation 2200 AU), HD 155555ABC (G5+K0+M4.5, 400 AU), HD 172555/CD − 64 1208 (A7+K7, 2000 AU), HR 7329AB (A0+M7, 200 AU), and HD 199143AB/BD −17 6128AB (primaries F8+K7, 15,000 AU; Kaisler et al. 2004).

Of these, the HD 172555/CD − 64 1208 system is remarkably similar to 51 Eri/GJ 3305. HD 172555 = HR 7012 is a mid-A star lying far to the southeast of the main OSCA concentrations in the sky (Fig. 1). Its spectral type has been variously classified as A2–A7; Houk & Cowley (1975) give A5 IV–V, while Gray & Garrison (1989) give A6 IV based on spectral line shapes. With a Hipparcos parallax distance of 29.2 ± 0.6 pc, an enormous proper motion oriented southward \( (\mu_\alpha, \mu_\delta) = (32.7, -148.7) \) mas yr\(^{-1}\), and a roughly measured radial velocity of \( +2 \pm 5 \) km s\(^{-1}\), its closest approach to the OSCA was 11 Myr ago when it lay \( \sim 29 \) pc from the Upper Centaurus-Lupus (UCL) subgroup.

This intermediate-mass star has a comoving companion CD − 64 1208 with spectral type M0, \( V = 10.4 \), and \( K = 6.1 \). Whereas the older literature did not indicate a relationship between 51 Eri and GJ 3305, various proper-motion surveys since Fallon (1983) showed that HD 172555 and CD − 64 1208 are approximately comoving. The most accurate proper motion for the M0 star is from the UCAC2 catalog with \( (\mu_\alpha, \mu_\delta) = (30.14, -153.3) \) mas yr\(^{-1}\), which is consistent with the A star. Only 0.04% of stars within \( \pm 2'/5 \) of HD 172555 have UCAC2 motions within \( \pm 20 \) mas yr\(^{-1}\) of its value.

A spectrum of CD − 64 1208 reported by Zuckerman et al. (2001a) shows H\( \alpha \) in emission with EW(H\( \alpha \)) = 2.2 A and strong lithium in absorption with EW(Li I \( 6708) = 0.58 \) A. Its X-ray emission is very strong, about 1 count s\(^{-1}\) in ROSAT proportional counter observations (Simon & Drake 1993), with a soft X-ray spectrum and strong extreme-ultraviolet emission. It is possibly the source of a soft X-ray flare seen with the early non-imaging Ginga satellite (Kreyling et al. 1995; Thomas et al. 1998; Forster et al. 1999). We have obtained a brief Chandra snapshot of the region with the ACIS detector (ObsID = 5180, 2004 March 10; not displayed here). The mid-A primary is not seen with a limit log \( L_X < 26.9 \) ergs s\(^{-1}\) (0.5–8 keV), but the M0 secondary is detected with \( \approx 0.2 \) counts s\(^{-1}\). The corresponding luminosity at \( d = 39 \) pc is log \( L_X \approx 29.5 \) ergs s\(^{-1}\). Similar to GJ 3305, this is near the top of the X-ray luminosity function for M dwarfs and indicates a very young age.

These two binary systems, 51 Eri/GJ 3305 and HD 172555/CD − 64 1208, share many properties: a (coincidental) distance of 30 pc from the Sun, a factor of 3–4 mass ratio, a projected separation of 2000 AU, very strong X-ray emission in the lower mass star, very high velocity proper motions pointed toward an origin in the OSCA, and a location of the lower mass star above the main sequence assuming it is co-distant with the higher mass star. They differ only in their distant locations from each other and the OSCA concentrations in the sky, and in the strength of the lithium line, which is 5 times stronger in CD − 64 1208 than in GJ 3305. Masciadri et al. (2005) have conducted a high-resolution
near-infrared imaging search for planetary companions around CD −64 1208; no gaseous companion with mass >5M_J was found with orbital radius >15 AU.

6. DISCUSSION

The evidence is clear that 51 Eri and GJ 3305 together are a young, wide binary system at d = 30 pc. The distance to 51 Eri is directly measured by parallax, and it has a high-velocity space motion that is convergent with the OSCA. GJ 3305 shares its unusual proper motion and is thus very unlikely (P < 0.0002) to be an unrelated star. Assuming a 30 pc distance, GJ 3305 lies on the ≃13 Myr isochrone on the H-R diagram. It exhibits moderately strong chromospheric emission and extreme X-ray emission with powerful X-ray flares. Its photometric variability is probably due to starspots modulated with a 6 day period. Its spectrum shows an abundance of lithium intermediate between the primordial levels seen in young T Tauri stars and the fully depleted main-sequence stars. From this confluence of evidence, we conclude with confidence that both 51 Eri and GJ 3305 are OSCA outliers with ages around 10–15 Myr similar to the UCL and LCC OSCA subgroups.

The main anomaly is the relatively weak Li i λ6708 line compared to other OSCA stars (Fig. 6 [bottom]). However, it is well known that ZAMS stars exhibit a wide range of lithium levels and there is growing evidence that a small fraction of M stars undergo rapid lithium depletion while on their PMS tracks. In addition to the BPMG stars discussed in § 2.2, Song et al. (2002) report a M4+M4.5 BPMG binary in which the two components show an order of magnitude difference in lithium line strength (EW = 300 mA and EW < 30 mA). A spectroscopic survey for lithium in ~10 Myr Orion Nebula Cluster stars shows a few lithium-depleted stars contemporaneous with the dominant population of undepleted stars (Palla et al. 2005). Conversely, a survey of the 35 Myr NGC 2547 cluster (Jeffries et al. 2003) reveals several stars with intermediate levels of lithium contemporaneous with the dominant population of lithium-depleted stars. Different theoretical models of M0 stellar interiors give very different predictions of lithium depletion in the 10–20 Myr age range (see Fig. 9 in Jeffries et al.). Detailed modeling of solar-mass PMS stars shows that slow or rapid lithium depletion in 10–20 Myr can readily be explained by small changes in convection zone properties (Paul & Turek-Chiézé 2002). It is thus reasonable to conclude that GJ 3305 is an OSCA member that experienced rapid depletion of lithium.

51 Eri and GJ 3305 lack significant K-band excesses and thus lack massive inner protoplanetary disks. Stars devoid of inner disks at t ≃ 10 Myr are known in other OSCA outlying groups, e.g., in the TWA (Uchida et al. 2004) and the η Cha cluster (Lyo et al. 2003), and have been inferred from the wide range of rotation rates measured in the Pleiades and other ZAMS clusters. Such stars are excellent candidates for searches for outer disks at mid-infrared wavelengths using the Spitzer Space Telescope and high spatial resolution surveys for Jovian-mass protoplanets.

Kinematic evidence indicates the binary system is an outlier of the OSCA, similar to members of the BPMG, TWA, η Cha cluster, and others shown in Figure 1. The 51 Eri system is the most distant member yet found, lying 100° in the sky and 110 pc in space from the rich LCC OSCA subgroup with age ~17 Myr (Mamajek et al. 2002). This is possible if the molecular cloudlet from which the 51 Eri system was formed was imparted a velocity of ~9 km s⁻¹ with respect to the more massive molecular cloud that formed the LCC subgroup. Such velocity differences are commonly seen in giant molecular cloud complexes that give rise to OB associations and can be imparted to disperse young stellar systems (Feigelson 1996). Yet the 51 Eri and GJ 3305 components could not have remained bound if they experienced a relative motion greater than 1 km s⁻¹. The HD 104237 quintet (Feigelson et al. 2003) and the HD 172555/CD −64 1208 binary are similarly dynamically fragile multiple systems among OSCA outliers.

The 51 Eri/GJ 3305 binary system is thus a valuable tool in several respects. It validates the use of kinematic extrapolations of motions across the sky to find OSCA outliers. It supports arguments for distributed star formation in turbulent giant molecular cloud complexes producing small stellar groups that disperse far from the rich OB associations. GJ 3305 can be studied as an example of rapid lithium depletion in PMS stars. Finally, as one of the closest stellar systems with an age comparable to the later phases of planet formation, both 51 Eri and GJ 3305 represent excellent laboratories for the search for older protoplanetary disks or recently formed protoplanets.

This work was supported by NASA contract AR5-6001X (G. Garmire). W. A. L. acknowledges support from a University of New South Wales at the Australian Defence Force Academy Special Research Grant. We thank L. W. Ramsey (Pennsylvania State University) for rapid access to the Hobby-Eberly Telescope, L. A. Crourse (SAAO), Charles Poteet (Western Kentucky University), John Cybulski, and Ethan Jordan (Pennsylvania State University) for assistance. The referee, Alex Brown (University of Colorado), provided very helpful commentary. The effort benefited from online data resources from the Centre des Données Stellaires (Strasbourg), Astrophysics Data System (Smithsonian Astrophysical Observatory), High Energy Astrophysics Science Archive Research Center (NASA-Goddard Space Flight Center), and the Infrared Space Archive (NASA-IPAC).

REFERENCES

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco: ASP), 127

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 2002, A&A, 382, 563

Barrado y Navascues, D., Stauffer, J. R., Song, I., & Caillault, J.-P. 1999, ApJ, 523, 521

Blaauw, A. 1991, The Physics of Star Formation and Early Stellar Evolution, ed. C. J. Lada & N. D. Kylafis (NATO ASI Ser. 342; Dordrecht: Kluwer), 125

Brandt, W. N., & Hasinger, G. 2005, ARAA, 43, 827

de Zeeuw, P. T., Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117, 354

Evans, D. W., Irwin, M. J., & Helmer, L. 2002, A&A, 395, 347

Fallon, F. W. 1983, Trans. Astron. Obs. Yale Univ. 32 (2), 1

Feigelson, E. D. 1998, ApJ, 468, 306

Feigelson, E. D., Lawson, W. A., & Garmire, G. P. 2003, ApJ, 599, 1207

Fleming, T. A., Schneider, J. H. M. M., & Giampapa, M. S. 1995, ApJ, 450, 401

Forster, K., Leighly, K. M., & Kay, L. E. 1999, ApJ, 523, 521

Freeman, P. E., Kashyap, V., Rosner, R., & Lamb, D. Q. 2002, ApJS, 138, 185

Fuhmeister, B., & Schmitt, J. H. M. M. 2003, A&A, 403, 247

Getman, K. V., et al. 2005, ApJS, 160, 319

Gizis, J. E., Reid, I. N., & Hawley, S. L. 2002, AJ, 123, 3356

Gray, R. O., & Garrison, R. F. 1989, ApJS, 70, 623

Hag, E., et al. 2000, A&A, 355, L27

Houck, N., & Cowley, A. P. 1975, Michigan Catalogue of Two-Dimensional Spectral Types for the HD Stars, Vol. 1 (Ann Arbor: Univ. Michigan)

Irwin, M., & McMahon, R. 1992, IAU Commission 9, 2, 31

Jeffries, R. D., Oliveira, J. M., Barrado y Navascues, D., & Stauffer, J. R. 2003, MNRAS, 343, 1271

Jeffries, R. D., & Tolley, A. J. 1998, MNRAS, 300, 331

This work was supported by NASA contract AR5-6001X (G. Garmire). W. A. L. acknowledges support from a University of New South Wales at the Australian Defence Force Academy Special Research Grant. We thank L. W. Ramsey (Pennsylvania State University) for rapid access to the Hobby-Eberly Telescope, L. A. Crourse (SAAO), Charles Poteet (Western Kentucky University), John Cybulski, and Ethan Jordan (Pennsylvania State University) for assistance. The referee, Alex Brown (University of Colorado), provided very helpful commentary. The effort benefited from online data resources from the Centre des Données Stellaires (Strasbourg), Astrophysics Data System (Smithsonian Astrophysical Observatory), High Energy Astrophysics Science Archive Research Center (NASA-Goddard Space Flight Center), and the Infrared Space Archive (NASA-IPAC).
Kaisler, D., Zuckerman, B., Song, I., Macintosh, B. A., Weinberger, A. J., Becklin, E. E., Konopacky, Q. M., & Patience, J. 2004, A&A, 414, 175
Kalas, P., Liu, M. C., & Matthews, B. C. 2004, Science, 303, 1990
Kenyon, S. J., & Hartmann, L. 1995, ApJS, 101, 117
Kharchenko, N. V., Piskunov, A. E., & Scholz, R.-D. 2004, Astron. Nachr., 325, 439
Koen, C., & Eyer, L. 2002, MNRAS, 331, 45
Kreysing, H.-C., Brunner, H., & Staubert, R. 1995, A&AS, 114, 465
Kroupa, P. 1998, MNRAS, 298, 231
Lagrange, A.-M., Backman, D. E., & Artymowicz, P. 2000, in Protostars and Planets IV, ed. V. Mannings et al. (Tucson: Univ. Arizona Press), 639
Lawson, W. A., Crause, L. A., Mamajek, E. E., & Feigelson, E. D. 2001, MNRAS, 321, 57
Lawson, W. A., Lyo A.-R., & Muzerolle J. 2004, MNRAS, 351, L39
Lyo, A.-R., Lawson, W. A., & Bessell M. S. 2004, MNRAS, 355, 363
Lyo, A.-R., Lawson, W. A., Mamajek, E. E., Feigelson, E. D., Sung, E.-C., & Crause, L. A. 2003, MNRAS, 338, 616
Mamajek, E. E., & Feigelson, E. D. 2001, in ASP Conf. Ser. 244, Young Stars Near Earth: Progress and Prospects, ed. R. Jayawardhana & T. Greene (San Francisco: ASP), 104
Mamajek, E. E., Lawson, W. A., & Feigelson, E. D. 1999, ApJ, 516, L77
Mamajek, E. E., Meyer, M. R., & Liebert, J. 2002, AJ, 124, 1670
Martín, E. L., Rebolo, R., Magazzù, A., & Pavlenko, Y. V. 1994, A&A, 282, 503
Masciadri, E., Mundt, R., Henning, T., Alvarez, C., & Barrado y Navascués, D. 2005, ApJ, 625, 1004
McCarthy, C., & Zuckerman, B. 2004, AJ, 127, 2871
Monet, D. G., et al. 2003, AJ, 125, 984
Muzerolle, J., Calvet, N., Briceno, C., Hartmann, L., & Hillenbrand, L. 2000, ApJ, 535, L47
Neuhäuser, R., Sterzik, M. F., Schmitt, J. H. M. M., Wichmann, R., & Krautter, J. 1995, A&A, 297, 391
Ortega, V. G., de la Reza, R., Jilinski, E., & Bazzanella, B. 2002, ApJ, 575, L75
———. 2004, ApJ, 609, 243
Palla, F., Randich, S., Flaccomio, E., & Pallavicini, R. 2005, ApJ, 626, L49
Piao, L., & Turek-Chièze, S. 2002, ApJ, 566, 419
Preibisch, T., Guenther, E., Zinnecker, H., Sterzik, M., Frink, S., & Roester, S. 1998, A&A, 333, 619
Preibisch, T., et al. 2005, ApJS, 160, 401
Ramsey, L. W., et al. 1998, Proc. SPIE, 3352, 34
Randich, S., Pallavicini, R., Meola, G., Stauffer, J. R., & Balchandran, S. C. 2001, A&A, 372, 862
Reiners, A., & Schmitt, J. H. M. M. 2003, A&A, 412, 813
Schmitt, J. H. M. M., & Liefke, C. 2004, A&A, 417, 651
Schonfeld, E. 1886, Bonner Durchmusterung des südlichen Himmels (Bon: Marcus & Weber)
Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593
Simon, T., & Drake, S. A. 1993, AJ, 106, 1660
Song, I., Bessell, M. S., & Zuckerman, B. 2002, ApJ, 581, L43
Stauffer, J. R., Caillault, J.-P., Gagne, M., Prosser, C. F., & Hartmann, L. W. 1994, ApJS, 91, 625
Stephenson, C. B. 1986, AJ, 91, 144
Sterzik, M. F., Acelá, J. M., Covino, E., & Petr, M. G. 1999, A&A, 346, L41
Thomas, H.-C., Beuermann, K., Reinsch, K., Schwöpe, A. D., Trumpler, J., & Voges, W. 1998, A&A, 335, 467
Townsley, L. K., Brooks, P. S., Garmire, G. P., Nousek, J. A. 2000, ApJ, 534, L139
Townsley, L. K., Feigelson, E. D., Montmerle, T., Brooks, P. S., Chu, Y., & Garmire, G. P. 2003, ApJ, 593, 874
Tull, R. G. 1998, Proc. SPIE, 3355, 387
Uchida, K. I., et al. 2004, ApJS, 154, 439
Voges, W., et al. 1999, A&A, 349, 389
Webb, R. A., Zuckerman, B., Plaitas, I., Patience, J., White, R. J., Schwartz, M. J., & McCarthy, C. 1999, ApJ, 512, L63
Weisskopf, M. C., Brinkman, B., Canizares, C., Garmire, G., Murray, S., & Van Speybroeck, L. P. 2002, PASP, 114, 1
Worley, C. E., & Douglass, G. G. 1997, A&A, 125, 523
Zapatero Osorio, M. R., Béjar, V. J. S., Pavlenko, Y., Rebolo, R., Allende Prieto, C., Martin, E. L., & García López, R. J. 2002, A&A, 384, 937
Zuckerman, B., Song, I., Bessell, M. S., & Webb, R. A. 2001a, ApJ, 562, L87
Zuckerman, B., Webb, R. A., Schwartz, M., & Becklin, E. E. 2001b, ApJ, 549, L233