σ ORIONIS IRS1 A AND B: A BINARY CONTAINING A PROPLYD

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ABSTRACT

We report optical and infrared imaging spectroscopy observations of the young binary object σ Orionis IRS1 A/B. The brighter component (σ Ori IRS1 A) of this binary system has M1 spectral type and a mass in the range of \(0.3 \pm 0.8\) M\(_\odot\). The fainter component (σ Ori IRS1 B) has a unique morphology and spectrum. The unresolved stellar object is surrounded by an extended envelope that is slightly offset from the position of this star. The envelope’s spectrum shows strong emission lines of H and He I but no shock-excited emission from H\(_2\) or [Fe II]. The embedded stellar object σ Ori IRS1 B has an absorption spectrum characteristic of a late M photosphere, but with an additional approximately equal amount of dust continuum flux veiling the absorption lines. The spectrum of σ Ori IRS1 B is probably a young brown dwarf embedded in a proplyd that is being photoevaporated by the UV flux of the nearby multiple O and B star system σ Ori.

Key words: stars: formation – stars: low-mass, brown dwarfs – stars: pre-main sequence

1. INTRODUCTION

The binary of the late O-star σ Ori was discovered by Struve (1837) using visual micrometer measurements. With the further discovery by Bolton (1974) that component σ Ori A is itself a spectroscopic binary, the determination of the orbit of components A and B by Heinze (1997) and the identification of the massive C, D, and E components (Caballero 2007a; Sherry et al. 2008), the σ Ori system is now viewed as somewhat analogous to the Trapezium system of massive stars in the Orion Nebula. The multiple star system σ Ori lies in the center of a small cluster of young lower mass stars, as first discussed by Garrison (1967). This cluster has \(\approx 300\) members with a total mass of 150–225 M\(_\odot\), with ages of individual members ranging from several million years (Sherry et al. 2008) down to stars in the outflow phase (Reipurth et al. 1998) and masses ranging from the massive members of the σ Ori group down to objects of possibly only planetary mass (Zapatero Osorio et al. 2008 and references therein). The properties of the σ Ori cluster have recently been reviewed by Walter et al. (2008) and we refer to references therein for more details. Sherry et al. (2008) arrived at a main-sequence-fitting distance of 420 pc, consistent with the distance to main Orion OB1b association. The extinction toward the σ Ori cluster is very low and can be neglected for work in the near infrared.

The discovery by van Loon & Oliveira (2003) of the infrared object σ Ori IRS1 about 3\(^\circ\) north of the high-mass binary σ Ori A/B, associated with extended infrared emission and coinciding with a VLA radio source (Drake 1990) raised the possibility that this object is a proplyd, similar to the many objects of this type found in the Orion nebula. σ Ori IRS1 has been detected in the near-infrared by Caballero (2005), and in X-rays by Sanz-Forcada et al. (2004), Caballero (2007b), and Skinner et al. (2008). The variability and the high temperature component in its X-ray spectrum are consistent with it containing a magnetically active low-mass T Tauri star. Infrared images using adaptive optics by Bouy et al. (2009) showed that σ Ori IRS1 is a double source with components IRS1 A and IRS1 B. In this Letter we present near-infrared integral-field spectroscopy of the two components of σ Ori IRS1.

2. OBSERVATIONS AND DATA REDUCTION

We had noticed the binary nature of σ Ori IRS1 independently from Bouy et al. (2009) during observations on 2007 December 30 (UT) using the Keck 2 telescope with the NIRCam near-infrared camera and natural guide star adaptive optics under non-photometric conditions. The image in the Br\(_\gamma\) filter is shown as part of Figure 1. We observed σ Ori IRS1 again with the OH-Suppressing Infrared Integral Field Spectrograph (OSIRIS; Larkin et al. 2006) at Keck 2 on the night of 2008 August 21, UT, under excellent weather conditions using the finest scale of 20 mas pixel\(^{-1}\). The quality of these observations allowed a detailed study of the σ Ori IRS1 B emission spectrum in the H and K windows (Figures 2 and 3) and the spectral classification of both components of the binary star system σ Ori IRS1 (Figures 4). For the K-band observations, we used spectra of the multiple O and B star system σ Ori A/B as the atmospheric absorption standard, after interpolation across the strong Br\(_\gamma\) absorption line, and multiplied the ratio spectra by the spectrum of a 30,750 K blackbody, the \(T_{\text{eff}}\) of an O9.5V star (Massey et al. 2005). We did not obtain calibration spectra of σ Ori A/B in the H band. Therefore, the H-band spectrum of σ Ori IRS1 B in Figure 2 used the M1 star σ Ori IRS1 A as the atmospheric absorption standard, and the ratio spectrum was multiplied by the spectrum of the M1V star HD42581 from the spectral library of Cushing et al. (2005), to establish the proper continuum. The spectrum in Figure 2 was separately flux calibrated in the H and K bands by multiplying the spectrum with the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) spectral response curves, integrating the flux, using the 2MASS flux calibration of Cohen et al. (2003), and then scaling the result to match the published H and Ks magnitudes of Bouy et al. (2009).

We also obtained optical seeing-limited slit-less spectroscopy using the Wide Field Grism Spectrograph 2 (WFGS2; Uehara et al. 2004) at the UH 2.2 m telescope in an effort to detect the H\(_\alpha\) line from σ Ori IRS1 B. The images were obtained on the night of 2008 October 11, UT, under near-photometric conditions. This wide-field collimator–camera system was used without a slit, with a narrow bandwidth H\(_\alpha\) filter (10 nm FWHM) as a
Figure 1. Slit-less spectrum of the σ Ori system, pre-filtered and centered around Hα. The brightest continuum is the binary σ Ori A/B with its late O to early B compound spectrum, with additional contamination from component σ Ori C. The spatial coordinates refer to the wavelength of Hα. The Hα absorption of the binary σ Ori A/B is clearly seen in the higher signal level window. The proplyd σ Ori IRS1 B is the object detected only by its Hα emission line to the north of the bright binary. The image to the right is the Keck NIRC-2 adaptive optics image of the σ Ori system in the Brγ+continuum filter, covering the area indicated by the box in the Hα image. The main components σ Ori A/B are visible behind the partly transparent occulting mask.

3. SPECTRAL CLASSIFICATION OF IRS1 A AND B

The median age of the σ Ori cluster is 2–3 Myr (Sherry et al. 2008), so that all low-mass objects are still contracting, and are therefore larger, more luminous, and have lower surface gravity than main-sequence stars. When attempting to classify their spectra, it is usually found that their features fall between those of luminosity class V and III, but closer to class V, as was shown in the early work by Hodapp & Deane (1993) and Greene & Lada (1996). In mid- to late-M spectral types, the ratio of the strength of the CO bandheads to that of the atomic lines, as well as the ratio of the two components of the Na doublet (see Figure 4), are luminosity dependent and the latter show that both σ Ori IRS1 components are indeed much closer to luminosity class V than to class III.

The spectral classification of the two components of σ Ori IRS1 relies on the strongest molecular feature in the atmospheric K window, the CO bandheads, and on the atomic line systems of Na, Ca, Mg, and the complex of Fe and Ti lines at 2.23 μm. The spectral classification was done by discussion of features in direct comparison (Figure 4) with the IRTF/SPEX spectral library of Cushing et al. (2005).

3.1. σ Ori IRS1 A

In the spectrum of IRS1 A in Figure 4 the absorption line systems of Na and Ca are of almost equal strength. The absorption line of Mg at 2.282 μm is clearly detected. This is most closely matched by the comparison spectrum of M1V type that also reproduces the shape of the Fe and Ti complex at 2.23 μm best. For later spectral types (M3V), the Mg line is too weak and the shortest wavelength component of the Ca feature becomes too strong. For even earlier spectral types, Mg becomes too strong, and the line ratios of the Ca and the Fe and Ti multiplets do not match σ Ori IRS1 A. The CO bandheads in IRS1 A are stronger compared to Na and Ca than in M1V spectral types, as it would be expected for an object of higher than main-sequence luminosity. We conclude that a spectral type of M1V is the closest match to the spectrum of IRS1 A with an uncertainty of one decimal subclass, the caveat being that IRS1 A is more luminous than a main-sequence object and that it is young. Following Luhman et al. (2003), this gives its effective temperature as 3705 ± 150 K.
Figure 3. Extracted adjacent continuum, line plus underlying continuum, and continuum-subtracted line images of σ Ori IRS1 A and B in the emission lines of He i (2.059 μm) and H Brγ (2.166 μm). Tickmarks are in units of the OSIRIS 20 mas pixels. The arrow indicates the direction toward the illuminating UV source σ Ori A/B. The X symbol in the continuum-subtracted images indicates the position of the star. It should be noted that σ Ori IRS1 A is unresolved and that all the structure seen around it is due to the PSF.

Figure 4. Continuum spectra of σ Ori IRS1 A and IRS1 B in the K window and comparison spectra from the IRTF spectral library (Cushing et al. 2005).

From the $K_s$ magnitude of 10.48 (Bouy et al. 2009) and with colors and bolometric corrections from Johnson (1965), we arrive at a rough estimate for the luminosity of σ Ori IRS1 A of 0.86 $L_\odot$. Comparison of these $T_{\text{eff}}$ and L data with the 1998 revisions of the D’Antona & Mazzitelli (1997) evolutionary tracks in Figure 5 places σ Ori IRS1 A on the track of a 0.3 $M_\odot$ star with a nominal age of 0.3 Myr. Compared to the 1 Myr isochrone of the Baraffe et al. (1998) and Chabrier et al. (2000) models σ Ori IRS1 A appears to be a star of 0.8 $M_\odot$ and an age of $\approx$1 Myr. The errors indicated in Figure 5 represent the uncertainty of $\pm 1$ subclass in spectral type determination, and the estimated total error from the uncertainty in bolometric corrections values (Malkov et al. 1997), color transformations, and photometric errors. As discussed both by D’Antona & Mazzitelli (1997) and Baraffe et al. (2002), the evolutionary models themselves are still quite uncertain at these young ages, adding another caveat to the interpretation of the results.

3.2. σ Ori IRS1 B

The best fit to the line ratios of σ Ori IRS1 B is a M7 or M8 star on the basis of the detection of Na lines and non-detection of Ca lines, and the ratio of Na to CO bandhead strength. However, all these late M class V stars have much stronger lines (both the Na and the CO bandhead lines) than σ Ori IRS1 B, so in order to match the spectrum, we have to postulate an additional, diluting continuum component to the spectrum. As we will discuss in detail in Section 4, the strong spatially extended Brγ and He i emission suggests that σ Ori IRS1 B is a proplyd in the process of being photoevaporated by UV radiation from the OB stars in the σ Ori A/B system. It is therefore reasonable to assume that some dust in the proplyd gets heated by UV absorption to temperatures near the sublimation point, and that its emission dilutes the photospheric emission from the embedded star. However, Figure 3 clearly shows that the line emission is more extended than the continuum, which appears unresolved. It is also possible that part of the hot dust emission originates much closer to the star and is powered by an accretion disk. Our data are not sufficient to uniquely identify a combination of dust opacity and temperature to best match the spectrum, but solutions with dust temperatures in the range of 1000 K and contributions of about 50% of dust emission to the total flux give good matches to the line depths. Figure 4 therefore compares the spectrum of σ Ori IRS1 B, expanded
by a factor of 2 to account for the dilution of the lines, with archival spectra of mid-M stars (above) and M8-L1 stars and an M7III star below. This comparison places the spectral type of σ Ori IRS1 B in the range from M6 to M9. A spectral type as early as M6 is consistent with the data when we consider that for lower gravity atmospheres, the Na is fainter and the CO bandheads are stronger than for main-sequence stars. On the other extreme, the M9 class is still compatible with the data, considering the substantial errors. A spectral type of M5 can be excluded with confidence, since the Ca feature would be present, as early as M6 is consistent with the data when we consider the substantial errors. A spectral type of M5 can be excluded since those types do not show Na absorption. We also plot the 1 Myr isochrone of the models by Baraffe et al. (1998) and Chabrier et al. (2000) and note that σ Ori IRS1 B is well above this isochrone. The differences between both models illustrate the problems with theoretical H–R diagrams at young ages that the authors of those models are well aware of Baraffe et al. (2002).

As an alternative to comparing with evolutionary models, we can compare σ Ori IRS1 B directly to the components of the young eclipsing binary 2MASS J05352184−0546085 in the Orion Nebula whose masses have been directly measured by Stassun et al. (2006). This star’s primary component of M6.5 ± 0.5 spectral type has a measured mass of 0.0541 M⊙, while the slightly hotter secondary component has a mass of 0.0340 M⊙. Since σ Ori IRS1 B is of later spectral type than either of the components of this eclipsing binary and is probably of similar age, it seems certain that σ Ori IRS1 B has a substellar mass below 0.05 M⊙. Finally, in a strong UV radiation environment, the photospheric temperature may be elevated above what an isolated object of otherwise identical properties might have, which would lead to an overestimate for the mass.

4. THE EMISSION LINE SPECTRUM OF σ ORI IRS1 B

The emission line spectrum in the H and K bands of σ Ori IRS1 B is shown in Figure 2. The spectrum is dominated by strong emission from the Brackett series of Hα and by emission lines of Hei. There is, however, no detectable emission from shock-excited H₂ in the S(1) lines, nor is there forbidden line emission in the 1.644 μm emission line of [Fe ii], which is often associated with outflow activity in young stars. Emission lines are one of the defining characteristics (Joy 1945) of classical T Tauri stars and in those stars originate from the accretion disk. In the case of σ Ori IRS1 B, however, our spatially resolved line images show that the Brγ and Hei emission lines do not originate in an accretion disk very close to the stellar surface. Rather, the line emission is spatially extended by 95 mas FWHM in the case of the Brγ line, and similar for Hei, while the point-spread function (PSF) is 55 mas FWHM. The brightest emission is offset toward the illuminating OB stars as illustrated in Figure 3. On the other hand, the emission lines do not show a pronounced bow-shock morphology, indicating that we are not seeing IRS1 B being illuminated side-on. This finding agrees with the morphology of the 10 μm emission found by van Loon & Oliveira (2003) who did not see the bow shock structure often found at 10 μm in side-on Orion proplyds by Smith (2005).

While the proplyd IRS1 B was easily detected in Hα emission, its surface brightness falls well short of the prediction by van Loon & Oliveira (2003) of being equal to the σ Ori A/B continuum in a 1 nm wavelength interval. Calibrating the continuum flux of σ Ori A/B against the spectrophotometry by Stone (1996) of the HST O9Vp calibration star HD93521, we get an Hα flux for the unresolved Hα emission knot from σ Ori IRS1 B of 4.7×10⁻¹⁵ Wm⁻². The dust that van Loon & Oliveira (2003) detected in thermal emission probably absorbs much of the Hα emission that would be expected based on extrapolation from the radio spectrum.

5. DISCUSSION

The formation of low-mass objects by photoevaporation of prestellar cores near massive stars has been discussed by Whitworth & Zinnecker (2004), and our data indicate that σ Ori IRS1 B appears to show this process in action. It is interesting

Figure 5. Pre-main-sequence evolutionary tracks from D’Antona & Mazzitelli (1997) (x symbols). Their Isochrones are labeled in units of 1000 yr. The 1 Myr isochrone from Baraffe et al. (1998) and Chabrier et al. (2000) is indicated by open squares. The H–R diagram loci of σ Ori IRS1 A and B are indicated. The error bars indicate the errors in spectral type determination and photometric errors.

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to note that the two components of the σ Ori IRS1 system show very different spectra. The more luminous component, IRS1 A, shows a pure photospheric absorption line spectrum without evidence for dust veiling or emission lines. Assuming that the two components are indeed physically close to each other, and that IRS1 A is therefore exposed to the same intense UV radiation field as IRS1 B, it can be concluded that IRS1 A must be without a disk or envelope. While distant encounters between stars in the dense cores of clusters are efficient at stripping the outer parts of disks (Pfalzner et al. 2005), the complete lack of any sign of circumstellar matter around the more massive component A of the IRS1 system can only be explained by dynamical effects within that system. It can be speculated that IRS1 A itself might be a very close binary whose formation may have destroyed the disk, in a scenario similar to those discussed by Reipurth (2000).

σ Ori IRS1 B is not the only object undergoing photoevaporation in the UV radiation field of σ Ori A and B. In a recent paper, Rigliaco et al. (2009) showed that the T Tauri star SO587 in the σ Ori cluster shows emission lines that can best be interpreted in a photoevaporation scenario.

6. CONCLUSIONS

We have obtained optical and near-infrared spectroscopy of the binary object σ Ori IRS1 A and B. Component σ Ori IRS1 A shows a pure photospheric absorption line spectrum of M1 type and is a low-mass star. Component B of the σ Ori IRS1 binary shows a compound dust and photospheric spectrum. After accounting for the dust continuum veiling, σ Ori IRS1 B itself can be classified as a M7 or M8 spectral type and probably is of substellar mass. Further, IRS1 B shows a strong emission line spectrum with the Brackett series of H and He I lines in the near infrared, and Hα in the optical. The line images in the Brγ and He I (2.06 μm) lines show that the source of the line emission is an extended envelope around the star. This envelope of σ Ori IRS1 B is clearly being photoevaporated by the UV radiation field of σ Ori A.

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REFERENCES

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 2002, A&A, 382, 563
Bolton, C. T. 1974, ApJ, 192, L7
Bouy, H., et al. 2009, A&A, 493, 931
Caballero, J. A. 2005, Astron. Nachr., 326, 1007
Caballero, J. A. 2007a, A&A, 466, 917
Caballero, J. A. 2007b, Astron. Nachr., 328, 917
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Cohen, M., Wheaton, Wm. A., & Megeath, S. T. 2003, AJ, 126, 1090
Cushing, M. C., Rayner, J. T., & Vacca, W. D. 2005, ApJ, 623, 1115
D’Antona, F., & Mazzitelli, I. 1997, Mem. Soc. Astron. Ital., 68, 807
Drake, S. A. 1990, AJ, 100, 572
Garrison, R. F. 1967, PASP, 79, 433
Greene, T. P., & Lada, C. J. 1996, AJ, 112, 2184
Heintz, W. D. 1997, ApJS, 111, 335
Hodapp, K.-W., & Deane, J. 1993, ApJS, 88, 119
Johnson, H. L. 1965, ApJ, 141, 170
Joy, A. H. 1945, ApJ, 102, 168
Larkin, J., et al. 2006, New Astron. Rev., 50, 362
Luhman, K. L., Stauffer, J. R., Muench, A. A., Rieke, G. H., Lada, E. A., Bouvier, J., & Lada, C. J. 2003, ApJ, 593, 1093
Malkov, O. Yu., Piskunov, A. E., & Shpil’kina, D. A. 1997, A&A, 320, 79
Massey, P., Puls, J., Pauldrach, A. W. A., Bresolin, F., Kudritzki, R. P., & Simon, T. 2005, ApJ, 627, 477
Pfalzner, S., Umbreit, S., & Henning, Th. 2005, ApJ, 629, 526
Reipurth, B. 2000, AJ, 120, 3177
Reipurth, B., Bally, J., Pesen, R. A., & Devine, D. 1998, Nature, 396, 343
Rigliaco, E., Natta, A., Randich, S., & Sacco, G. 2009, A&A, 495, L13
Sanz-Fernández, J., Franciosini, E., & Pallavicini, R. 2004, A&A, 421, 715
Sherry, W. H., Walter, F. M., Wolk, S. J., & Adams, N. R. 2008, AJ, 135, 1616
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Smith, N., Bally, J., Shaping, R. Y., Morris, M., & Kassis, M. 2005, AJ, 130, 1763
Stassun, K. G., Mathieu, R. D., & Valenti, J. A. 2006, Nature, 440, 311
Stone, R. P. S. 1996, ApJS, 107, 423
Struve, F. G. W. 1837, Astron. Nachr., 14, 249
Uchida, M., et al. 2004, Proc. SPIE, 5492, 661
van Loon, J. Th., & Oliveira, J. M. 2003, A&A, 405, L33
Walter, F. M., Sherry, W. H., Wolk, S. J., & Adams, N. R. 2008, in Handbook of Star Forming Regions, Vol. I, ed. B. Reipurth (San Francisco, CA: ASP), 732
Whitworth, A. P., & Zinnecker, H. 2004, A&A, 427, 299
Zapatero Osorio, M. R., et al. 2008, A&A, 477, 895