Are isolated planetary-mass objects really isolated?

A brown dwarf-exoplanet system candidate in the \( \sigma \) Orionis cluster

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ABSTRACT

Context. Free-floating planetary-mass objects have masses below the deuterium burning mass limit at about 13 Jupiter masses, and have mostly been found in very young open clusters. Their origin and relationship to stars and brown dwarfs are still a mystery.

Aims. The recent detection by direct imaging of three giant planets at wide separation (50–250 AU) from their primaries has raised the question about the “true isolation” of planetary-mass objects in clusters. Our goal was to test the possibility that some free-floating planetary-mass object could in fact be part of wide planetary systems.

Methods. We searched in the literature for stellar and brown-dwarf member candidates of the \( \sigma \) Orionis cluster (\( \sim 3 \) Ma, \( \sim 360 \) pc) at small angular separations from published candidate planetary-mass objects. We found one candidate planetary system, SE 70, composed of an X-ray source and a planetary-mass object, namely S Ori 68, separated by only 4.6 arcsec. In order to assess the cluster membership of the X-ray source, we obtained mid-resolution optical spectroscopy using ISIS on the William Herschel Telescope. We also compiled additional data on the target from available astronomical catalogues.

Results. We have found that SE 70 follows the spectrophotometric sequence of the cluster and displays spectroscopic features of youth, such as lithium in absorption and chromospheric H\( \alpha \) emission. The radial velocity is consistent with cluster membership. Hence, SE 70 is very probably a \( \sigma \) Orionis cluster member. The projected physical separation between SE 70 and S Ori 68 is 1 700\( \pm \)300 AU at the distance of the cluster. If the common proper motion is confirmed in the near future, the system would be composed of an M5–6 brown dwarf with an estimated mass of \( \sim 45 \text{ M}_\text{Jup} \) and an L5\( \pm \)2 giant planet with an estimated mass of \( \sim 5 \text{ M}_\text{Jup} \). It would be the widest and one of the lowest-mass planetary systems known so far.

Key words. stars: low mass, brown dwarfs – planetary systems – open clusters and associations: individual: \( \sigma \) Orionis

1. Introduction

Planetary-mass objects (PMOs) were directly detected for the first time in the \( \sigma \) Orionis cluster and in other very young star-forming regions (Zapatero Osorio et al. 2000; Lucas & Roche 2000; Najita et al. 2000). Recent discoveries suggest that PMOs are abundant in clusters and include the detection of objects with masses potentially as low as \( \sim 3 \) Jupiter masses (\( \text{M}_\text{Jup} \)) (Zapatero Osorio et al. 2002c; Lucas et al. 2005). Furthermore, observations suggest that many PMOs are surrounded by discs (Luhman et al. 2005). Although cluster PMOs have masses below the deuterium-burning mass limit (\( \sim 13 \text{ M}_\text{Jup} \); Chabrier & Baraffe 2000), they have not achieved the “grade” of exoplanet because they appear to float freely in the intracluster medium, far from the gravitational link to other star cluster members. The direct detection of planetary-mass candidates around a brown dwarf of the TW Hydrae association (Chauvin et al. 2004 – at a projected physical separation of 55 AU) and around the stars AB Pictoris and GQ Lupi (Chauvin et al. 2005 – 250 AU; Neuhäuser et al. 2005 – 100 AU) presents the opportunity to photometrically and spectroscopically characterize exoplanets at orbital separations much larger than those indirectly detected with radial velocity surveys (the radial velocity exoplanet candidate with the largest semi-major axis is 55 Cnc d, with \( a = 5.3\pm0.9 \) AU; Marcy et al. 2002). The discussion on how PMOs in wide orbits can be formed has been fed by the recent discovery of the system Oph 162225–240515 AB (240 AU) in the 1 Ma-old Ophiuchus region, which may be a very low-mass brown dwarf and a PMO pair (Jayawardhana &...
Nevertheless, the proximity between SE 70 and S Ori 68 motivated us to characterize in more detail the physical properties of the primary. We have taken intermediate-resolution optical spectroscopy and have compiled astrometric and photometric data of SE 70 to test more rigorously the hypothesis of membership in the σ Orionis cluster.

2. Observations and data mining

2.1. Optical spectroscopy

On 2006 February 4, we used the red arm of ISIS at the 4.2 m William Herschel Telescope (WHT) at the Observatorio del Roque de los Muchachos to obtain four mid-resolution spectra of SE 70. ISIS is a high-efficiency, double-armed, medium-resolution (8–120 Å mm\(^{-1}\)) spectrograph. The detector mounted on the red arm of ISIS is a Marconi2 with a 4610 pixel axis along the dispersion direction. The four spectra covered the wavelength range 6200–7100 Å (central \(\lambda = 6561\) Å), which allowed us to study the H\(\alpha\) and Li\(\beta\) 6707.8 spectroscopic features, and also to estimate both the spectral type and the radial velocity of the object. Nominal dispersion with the red grating with 1200 rulings mm\(^{-1}\) (R1200R) was 16.6 Å mm\(^{-1}\), which together with the 1.0-m slit led to a spectral resolution \(R \sim 3000\). The seeing was good (0.6–0.8 arcsec) and the sky was fairly clean. The total exposure time of the final co-added spectrum was 4 × 1800 s = 2 h. The spectra reduction was typical, with bias subtraction, flat correction, wavelength calibration (with arc spectra taken at the same position of the standard star – HD 289002, B3V – just before and after SE 70). The whole wavelength interval of the final combined spectrum of SE 70 is shown in the top window of Figure 1.

We estimated the spectral type of SE 70 at M5±1 from the calculation of the following spectral indices: \(PC1, I1, I2, I3\) (Martín, Rebolo & Zapatero Osorio 1996; Martín & Kun 1996). All of them are based on the ratio between the spectral fluxes at two different wavelengths, which roughly provides the slope of the spectral energy distribution in the red optical range. Calculated indices from the co-added SE 70 spectrum were compared to a grid of indices for different spectral types (early to late M) and luminosity classes (V to III). The dwarf class provided the best fit. The spectral types determined for each index were in the range M4.0 to M6.5, M5.0 being the most probable spectral type. This value is between 1.0 and 1.5 spectral subtypes earlier than expected from the \(J\)-band magnitude of SE 70 for a cluster member (see next section), but is consistent within the error bars. It should be noted that it is difficult to tightly constrain the spectral type from such a short wavelength interval, which allows us to use only a limited number of spectral type indicators. The strength of the titanium and vanadium oxide bands and the increasing slope of the spectrum redwards of 6900 Å provide further proofs of the relatively late spectral type of SE 70.

The H\(\alpha\) \(\lambda 6562.8\) atomic feature is in emission. All the M-type stars and brown dwarfs in the σ Orionis cluster with available spectroscopy display H\(\alpha\) in emission (see, for example, Zapatero Osorio et al. 2002a; Caballero 2006 – this fact is also
We have also detected Li\textsc{i} \(\lambda6707.8\) in absorption, with a pseudo-equivalent width, \(\text{pEW}(\text{Li}\textsc{i})\), of \(+0.60\pm0.10\) \AA. This value is similar to those of other members of the \(\sigma\) Orionis cluster with intermediate M spectral type (Zapatero Osorio et al. 2002a; Kenyon et al. 2005). Since objects of this spectral type destroy all their lithium through nuclear reactions in only a few megayears, it is derived that SE 70 is an extremely young M-type object with an age between 1 and \(~10\) Ma (the minimum and maximum ages for the \(\sigma\) Orionis cluster are 1 and 8 Ma, respectively).

Using the atomic features that are visible in the wavelength interval studied, H\textsc{r}, Li\textsc{i} and some Fe\textsc{i} lines, and the heads of some titanium oxide bands, we have estimated the radial velocity of SE 70 at about 40 km s\(^{-1}\) (the heliocentric velocity correction for the mean time of observation was \(-25.3\) km s\(^{-1}\)). If, assuming a conservative uncertainty of 25\%, the estimated value is consistent with other more precise determinations of the mean radial velocity of the cluster found in the literature (at about 30–35 km s\(^{-1}\) – Walter et al. 1998; Zapatero Osorio et al. 2002a; Muzerolle et al. 2003; Kenyon et al. 2005; Birmingham et al. 2005; Caballero 2006; Jeffries et al. 2006 – group 1). H\textsc{r} emission, if not chromospheric, could be blue-/redshifted, which would introduce an additional source of uncertainty into our measurement. We have also determined the radial velocity of SE 70 with respect to several emission lines that may be adsorbed to the nebulosity in the line of sight, and that are probably associated with the star-forming region. The difference between both radial velocities is null with an accuracy of 5 km s\(^{-1}\).

In Table I we summarize the measurements mentioned above (spectral type, H\textsc{r} and Li\textsc{i} pseudo-equivalent widths and radial velocity of SE 70). For completeness, the spectral type and H\textsc{r} pseudo-equivalent width upper limit from Barrado y Navascués et al. (2001) of S Ori 68 are also provided. Spectra with higher signal-to-noise ratio for both objects would be desirable for confirming membership to the \(\sigma\) Orionis cluster.

### 2.2. Additional data

The coordinates of the optical and near-infrared counterparts of SE 70 in the 2MASS, DENIS and USNO-B1.0 catalogues match between them with a precision better than 0.1 arcsec. Coordinates of this target in the discovery paper by Scholz & Eisloffel (2004) do not deviate from those of 2MASS by more than 0.5 arcsec. Those authors did not reported SE 70 to be a photometric variable in the \(I\) band and estimated an upper limit of 0.035 mag for its photometric stability. They announced an optical magnitude of \(I = 16.60\) mag, which led to a comparatively blue \(I - J_{\text{2MASS}}\) colour for its magnitude if it is cluster member. However, based on \(I\)-band data from DENIS catalogue, we determine an \(I - J\) colour of 1.80±0.13 mag, which locates this source on the bluest part of the spectrophotometric cluster sequence in the \(I\) vs. \(I - J\) colour–magnitude diagram, in the region of other M5–7 cluster members with lithium in absorption (Figure 4). SE 70 was not selected as a photometric candidate during other optical searches in the area (Béjar et al. 1999, 2001; Kenyon et al. 2005). Some bright brown-dwarf
cluster members with proven membership, such as the classical T Tauri substellar analogue S Ori J053825.4–024241, display quite blue colours in the red optical and had also escaped previous searches (Caballero et al. 2006).

Additional photographic B- and R-band and [3.6]-, [4.5]-, [5.8]- and [8.0]-band photometry has been taken from the USNO-B1.0 catalogue and the IRAC/Spitzer Telescope archive, respectively (see Caballero et al., in prep., for the latter). In Table 2 we provide all the collected photometry of several times larger than the cluster velocity dispersion. The automatic proper motion determination at the faint optical magnitudes 

### Table 2. Astrometric and photometric data of SE 70 and S Ori 68

|         | SE 70    | S Ori 68  |
|---------|----------|-----------|
| α       | 05 38 38.89 | 05 38 39.1 |
| δ       | –02 28 01.6 | –02 28 05 |
| μαcosδ   | –14±7     | —          |
| μδ       | +8±3      | —          |
| B        | 20.68±0.56 | —          |
| R        | 19.05±0.24 | —          |
| I        | 17.07±0.12 | 23.77±0.17 |
| J        | 15.27±0.04 | 20.2±0.3   |
| H        | 14.73±0.05 | —          |
| Ks       | 14.43±0.07 | 18.4±0.3   |
| [3.6]    | 14.06±0.14 | —          |
| [4.5]    | 14.07±0.17 | —          |
| [5.8]    | 13.76±0.19 | —          |
| [8.0]    | 13.8±0.3   | —          |

\(\alpha, \delta (J2000)\) and \(JHK_s\) magnitudes from 2MASS (Cutri et al. 2003); \(B\) (averaging two detections) and \(R\) magnitudes (averaging two double detections) and tangential velocities \(\mu_\alpha\) and \(\mu_\delta\) from USNO-B1.0 catalogue (Monet et al. 2003); \(I\) magnitude from DENIS catalogue (The DENIS Consortium); \(Spitzer\)-band magnitudes from Caballero et al. (in prep.).

|         | SE 70     | S Ori 68  |
|---------|-----------|-----------|
| BFHK    | 17.07±0.12 | 23.77±0.17 |
| BFHK    | 15.27±0.04 | 20.2±0.3   |
| BFHK    | 14.73±0.05 | —          |
| BFHK    | 14.43±0.07 | 18.4±0.3   |
| BFHK    | 14.06±0.14 | —          |
| BFHK    | 14.07±0.17 | —          |
| BFHK    | 13.76±0.19 | —          |
| BFHK    | 13.8±0.3   | —          |

\(\alpha, \delta (J2000)\) and \(IJK\) magnitudes from Zapatero Osorio et al. (2000).

### Table 2. Astrometric and photometric data of SE 70 and S Ori 68

Table 2 also provides the astrometry of SE 70. Coordinates indicate that it is located at about 8 arcmin to the O9.5V star that gives the name to the cluster, \(\sigma\) Ori A (and which is roughly the centre of mass of the cluster). Tangential velocities in \(\alpha\) and \(\delta\) have been taken from the USNO-B1.0 catalogue. The difference between the proper motions of SE 70 and \(\sigma\) Ori A is as large as \((\Delta \alpha, \Delta \delta) = (–19±7, +8±3)\) mas a\(^{-1}\). These values are several times larger than the cluster velocity dispersion. The automatic proper motion determination at the faint optical magnitudes has been taken from the USNO-B1.0 catalogue. The derived values of the position angle and the component of the proper motion along the line of sight, \(\mu_\alpha\) and \(\mu_\delta\), respectively, are given in Table 2. Coordinates \(\alpha\) and \(\delta\) (J2000) and \(IJK\) magnitudes from Zapatero Osorio et al. (2000).
nitudes of SE 70, fainter than the completeness $BR$-band magnitudes of the USNO-B1.0 catalogue, may lead to unreliable tangential velocities or to underestimated error bars. This is probably the case of SE 70. A simple inspection of the tangential velocity values of several faint spectroscopically confirmed members of the $\sigma$ Orionis cluster supports this hypothesis (they also display proper motions that are abnormally different from zero).

3. Discussion

Except for the unreliable astrometric measurement, all the studied astrometric parameters indicate that SE 70 is a bona fide non-accreting $\sigma$ Orionis cluster member: it displays X-ray emission, chromospheric H$\alpha$ emission, Li $i$ in absorption and radial velocity similar to those of the cluster and of the nebulousity, and lies on the spectrophotometric cluster sequence. The derived spectral type is on the borderline between very low-mass stars and brown dwarfs in $\sigma$ Orionis. However, the $J$-band magnitude of SE 70, which marks the peak in the spectral energy distribution, is about 1.0 mag fainter than those of the most massive brown dwarfs in the cluster (at the hydrogen-burning mass limit, $\sim 75 M_{\text{Jup}}$; Béjar et al. 2001; Caballero et al. 2004). Following our procedure for mass determination in the substellar domain, detailed in Caballero (2006)$^1$, we estimate SE 70 to be a brown dwarf with a mass of $45 M_{\text{Jup}}$. Hence, S Ori 68 and SE 70 may form a system whose masses resemble those of the Chauvin et al. (2004) 2MASS J1207334–393254 system (about 45 + 5 $M_{\text{Jup}}$ in the case of SE 70 + S Ori 68 versus about 25 + 5 $M_{\text{Jup}}$ in the case of 2M1207–39 + 2M1207–39b). However, the projected physical separation of the hypothetical $\sigma$ Orionis planetary system is about 30 times larger than that of 2M1207–39, and about seven times larger than that of AB Pic and Oph 162225–240515. Due to the low mass and the wide separation of the SE 70 + S Ori 68 system, it has the lowest gravitational binding energy among the considered planetary systems. Given the relatively high spatial density of cluster members in $\sigma$ Orionis and the weak bounding between SE 70 and S Ori 68, it seems dubious that the system can survive the tidal field within the cluster. The existence of a binary system with these characteristics is evidently a challenge for present ultra low-mass star forming scenarios, which predict tighter and more massive binary/planetary systems.

There is the possibility of the pair being a visual projection of two unrelated cluster members at slightly different heliocentric distances and hence not being a truly binary system. This is in contradiction with the statistical analysis performed by Caballero (in prep.), who has studied the spatial distribution of all the stellar population and the highest-mass domain of the brown-dwarf population in the $\sigma$ Orionis cluster. He has shown that 95% of the studied cluster member candidates at angular separations to $\sigma$ Ori A between 5 and 10 arcmin have their nearest neighbourhood at more than 10.9 arcsec (the SE 70 + S Ori 68 system is at about 8 arcmin to the cluster centre).

Among the more than 400 cluster member candidates studied from a 2MASS + DENIS correlation, none has a nearest neighbour closer than 7.1 arcsec, while the separation between SE 70 and S Ori 68 is only 4.6 arcsec. Figure 4 illustrates this discussion, and indicates that the SE 70 + S Ori 68 pair has less than about 1% probability to be a chance visual alignment. There are stellar pairs in the $\sigma$ Orionis cluster with smaller separations between components, but they are spectroscopic binaries (e.g. OriNTT 429; Lee et al. 1994) or very tight binaries unresolved by 2MASS or DENIS (e.g. $\sigma$ Ori A and $\sigma$ Ori B – 0.250 arcsec; $\sigma$ Ori AB and $\sigma$ Ori IRS1 – 3.32 ± 0.15 arcsec; HD 37525 A and HD 37525 B – 0.47 ± 0.04 arcsec; [W96] 4771–899 A and [W96] 4771–899 B – 0.40 ± 0.08 arcsec; Caballero 2005)$^2$.

It is not the aim of this paper to prove beyond doubt the cluster membership of the planetary-mass candidate S Ori 68. In order to do that, high-quality mid-resolution near-infrared

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$^1$ The mass is derived from the comparison between theoretical luminosities of Chabrier et al. (2000) and the luminosities of the objects. The latter are computed from the $J$-band absolute magnitude and an $I - J$ colour-dependent bolometric correction.

$^2$ The tight pair [W96] 4771–899 AB and [W96] 4771–899 C (aka S Ori J053847.7–022711, at $\rho = 7.63 \pm 0.10$ arcsec) is in fact a triple stellar system. There is an additional binary system candidate formed by a very low-mass star, S Ori J0539268–026614, and a faint brown dwarf at 4.4 arcsec ($J = 16.21 \pm 0.09$ mag, not found in 2MASS or DENIS catalogues). Both of them show Li $i$ in absorption (Zapatero Osorio, Béjar et al. in prep.).
spectra of S Ori 68 should be taken to detect low-gravity spectral features in the absorption atomic lines of alkalis, such as sodium or potassium. These features have been already found in several spectra of young brown dwarfs (e.g. Gorlova et al. 2003). To date, this study may only be accomplished, and with a time-consuming effort, with instruments such as LRIS at the Keck Observatory. Given the extraordinary faintness of S Ori 68 in the red optical range (I = 24 mag, R > 26–27 mag; S Ori 68 has the same I- and J-band magnitudes as S Ori 66, an intermediate-L planetary-mass object in σ Orionis with Hα in moderate emission), the detection of lithium in absorption in an optical spectrum is practically out of the question with present instrumentation.

Further ultra-accurate proper motion studies are needed to verify that both S Ori 68 and SE 70 form a common proper motion system. The Ori OB1b Association is in the solar antapex, moving in the opposite direction with respect to the Sun. Hence, the tangential velocities of the stellar members of the association are very low, less than 5 mas a\(^{-1}\) according to de Zeeuw et al. (1999). Confirmation of the common proper motion would require an accuracy of a few hundred milliarcsec. Such accurate measurements on very faint objects only will be achievable with technology of the near future, such as the Large Binocular Telescope and the LINC-NIRVANA instrument. It could be also done with the Hubble Space Telescope if a large enough time baseline is used. However, it could not be done with the GAIA satellite, because of faintness of targets in the optical.

Radial velocity measurements of the pair obtained with current or future near-infrared high-resolution spectrographs attached to ≥10-m-class telescopes, like NIRSPEC/Keck or NAHUAL/Gran Telescopio Canarias (Martín et al. 2005), might be able to constrain the binding status of the SE 70 – S Ori 68 system. These measurements must be more precise than 1 km s\(^{-1}\) to disentangle the common proper motion of the hypothetical binary system and the velocity dispersion of the σ Orionis cluster (that is of the order of 2.4 km s\(^{-1}\) – Caballero 2005). To illustrate the capabilities of NIRSPEC/Keck, Martín et al. (2006) reached a precision of 360 m s\(^{-1}\) in the radial velocity determination of the M9V-type brown dwarf LP 944–20.

4. Summary

We report on the analysis of a probable a brown dwarf–exoplanet system candidate in the σ Orionis cluster, formed by SE 70 and S Ori 68. The projected physical separation between them is 1 700±300 AU at the distance to the cluster. We have derived the spectral type of the primary (in the M5–6 interval) and found spectroscopic features typical in other young members of the σ Orionis cluster: lithium in absorption, Hα in (probably chromospheric) emission and radial velocity similar to the mean radial velocity of the cluster. Franciosini et al. (2006) had previously found the primary to be an X-ray emitter that underwent a flare during their observations. From an analysis of the spatial distribution of the cluster, if S Ori 68 is also a cluster member, there is about a 99% probability that they form a real planetary system. If this is the case, not all “isolated” planetary-mass objects are really isolated, and some planetary systems may have separations as wide as those of binary stellar systems.

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