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Direct detection of the companion of χ^1 Orionis

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Abstract. We present an H-band image of the companion of χ^1 Orionis taken with the Keck adaptive optic system and NIRC 2 camera equipped with a 300 mas-diameter coronographic mask. The direct detection of this companion star enables us to calculate dynamical masses using only Kepler's laws ($M_A = 1.01 \pm 0.13\ M_\odot$, $M_B = 0.15 \pm 0.02\ M_\odot$), and to study stellar evolutionary models at a wide spread of masses. The application of Baraffe et al. (1998) pre-main-sequence models implies an age of 70–130 Myrs. This is in conflict to the age of the primary, a confirmed member of the Ursa Major Cluster with a canonical age of 300 Myrs. As a consequence, either the models at low masses underestimate the age or the Ursa Major Cluster is considerably younger than assumed.

1. Introduction

χ^1 Ori is a G0V-star and is known to be a single-lined spectroscopic and astrometric binary. The orbital parameters were first derived by Lippincott & Worth (1978). Since then Irwin & Walker (1982) published precise radial-velocity measurements of the orbit. Gatewood (1994) published an astrometric parallax of the orbit of χ^1 Ori. Recently, Han & Gatewood (2002) using their new astrometric data and the radial velocity data from Marcy & Butler (1992,1998) presented a period of $P = 5156.7 \pm 2.5$ days and a mass ratio $q = M_B/M_A = 0.15 \pm 0.005$. McCarthy (1986) claimed to have detected the companion directly by speckle imaging techniques, but this has not been confirmed yet. They derive $M_V = 6.1$ mag, which would place the companion star to χ^1 Ori about 4 mag above the main sequence (Henry et al. 1999). Han & Gatewood (2002) claim that McCarthy (1986) and subsequent attempts by speckle observations have not been able to detect the companion directly due to instrument limitations.

The G-type star χ^1 Ori and its companion form a binary with a very small mass ratio. A direct detection of the secondary would be significant as it would allow the masses to be determined without astrophysical assumption. The derived mass and observed luminosity allow the age to be inferred from comparison to pre-main-sequence evolutionary tracks, which in turn enables a calibration of other alternate estimators.

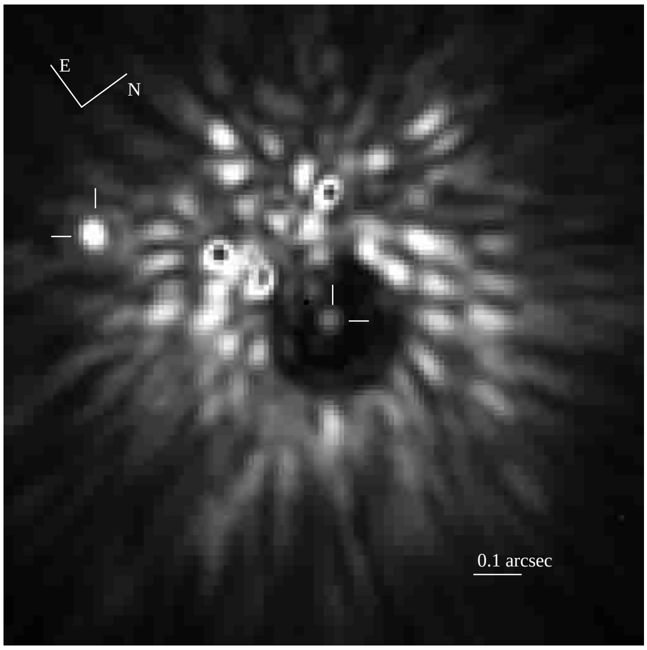

Fig. 1. The H-band image of χ^1 Ori behind the coronograph in the center and the companion to the left. Note the diffraction ring around the companion.

2. Data reduction and analysis

We observed χ^1 Ori on Feb. 28, 2002, using the Keck 2 telescope equipped with the NIRC2 camera and the adaptive optic system (Wizinowich et al. 2000), an H-band filter and a 300 mas diameter coronograph. The coronograph is semi-transparent with a throughput slightly below half a percent as determined by us (different from what is given in the manual, but confirmed by the Keck staff), so the position of the star behind it can be measured precisely. The total integration time was 0.18 s. The *FWHM* of the companion is 50 mas.

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We performed the data reduction, using the reduction software MIDAS (1991) provided by ESO. We divided the image by a normalized master sky-flat. We subtracted the background of χ^1 Ori B depending on the distance from χ^1 Ori A: χ^1 Ori B is located in the PSF wing of the component A which causes the main contribution to the background emission. To obtain a background subtracted instrumental magnitude of B we subtract an azimuthal averaged background (a one pixel wide annulus around A excluding B) for each pixel used.

We determined the magnitude of the companion as well as that of two stars used as photometric standards: the UKIRT faint standard FS 11, $H = 11.276 \pm 0.003$ mag (Hawarden et al. 2001) and TWA-5B, $H = 12.14 \pm 0.06$ mag (Lowrance et al. 1999). The standards were observed in the same night, and analyzed with the same procedure. We used 121 different aperture sizes starting with the brightest central pixel and calculating a background subtracted peak-to-peak flux ratio and then consecutively adding the next brightest pixel until we end up with a $121 = 11 \times 11$ pixel aperture box. For aperture sizes from 1 to 50 pixels, the resulting instrumental magnitude did not change significantly, so we use this value. By comparing the background subtracted instrumental magnitude of the companion to the background subtracted instrumental magnitudes obtained for TWA-5 B and FS 11, we measure the apparent H-band magnitude for the χ^1 Ori companion of 7.70 ± 0.15 mag, taking into account also the slightly different *FWHM* and Strehl ratios. With the Hipparcos parallax for χ^1 Ori of 115.43 ± 1.08 mas, we obtain $M_H = 8.01 \pm 0.15$ mag for the B-component.

3. Dynamical masses of χ^1 Orionis A & B

Using the orbital elements for χ^1 Ori published by Han & Gatewood (2002) ($i = 95.937 \pm 0.790$ deg, T_0(JD) $= 2\,451\,468.2 \pm 3.083$, $P = 5156.291 \pm 1.508$ days, $e = 0.452 \pm 0.002$), we can calculate the absolute masses of χ^1 Ori A and B directly using Kepler's laws. The measured apparent separation between the components A and B is $\rho = 0.4976 \pm 0.0036$ arcsec using a pixel-scale of 0.009942 ± 0.000500 arcsec/pixel as determined by the NIRC 2 team (Campbell, priv. comm.). The physical separation then is $r = 4.33 \pm 0.08$ AU. This results in a mass for the primary of $M_{\rm A} = 1.01 \pm 0.13\ M_\odot$ and for the secondary of $M_{\rm B} = 0.15 \pm 0.02\ M_\odot$. Using the parallax determined by Han & Gatewood (2002) of χ^1 Ori of 115.69 ± 0.74 mas, the masses would be $M_{\rm A} = 1.02 \pm 0.08\ M_\odot$ and $M_{\rm B} = 0.15 \pm 0.01\ M_\odot$. The error-bars are fairly large but further direct measurements will improve the orbital solution, in particular the separation and the position of the orbit in the sky. The position angle between χ^1 Ori A and B on the observing date (MJD = 52334.33952) is $(123.22 \pm 0.12)^\circ$. The observed position and position angle is only 13 mas and 2.8° away from the predicted values by Han & Gatewood (2002).

4. Spectral synthesis analysis of χ^1 Orionis

The basic stellar parameters of χ^1 Ori A are derived from a model atmosphere analysis of high resolution, high S/N échelle spectra (Figs. 2 and 3) obtained in January 2000 at the Calar Alto Observatory, Spain, 2.2 m telescope with FOCES (Pfeiffer et al. 1998). The fairly high projected rotational velocity $v \sin i = 8.7 \pm 0.8$ km s^{-1}, the strong lithium feature at $\lambda 6707$ (Fig. 3), the "dipper-star-like" kinematics ($U/V/W$ = 24/7/0 km s^{-1}), and the filled-in line cores of H$_\alpha$ (Fig. 2) and the Ca II infrared triplet all consistently confirm that χ^1 Ori must belong to the Ursa Major Cluster. As in Fuhrmann et al. (1997) we deduce the effective temperature of the primary, $T_{\rm eff} = 5920 \pm 70$ K, from the Balmer line wings and the surface gravity, $\log g = 4.39 \pm 0.10$, from the iron ionization equilibrium and the wings of the Mg Ib lines. We find the metallicity to be slightly below the solar value ([Fe/H] $= -0.07 \pm 0.07$), again very typical for the mean abundance of Ursa Major Cluster stars of $\langle$[Fe/H]$\rangle = -0.09$ (Boesgaard & Friel 1990). With a bolometric magnitude $M_{\rm bol} = 4.60 \pm 0.05$, and $T_{\rm eff}$ and [Fe/H] as derived above, we find the mass to be $M = 1.04\ M_\odot$ (implied from the tracks given in Fuhrmann et al. 1997), i.e. slightly above solar and with an uncertainty of about 0.05 $M_\odot$. The secondary – being more than five magnitudes (extrapolating the measured H-band magnitude) fainter in the visible – does not have an impact on our spectra.

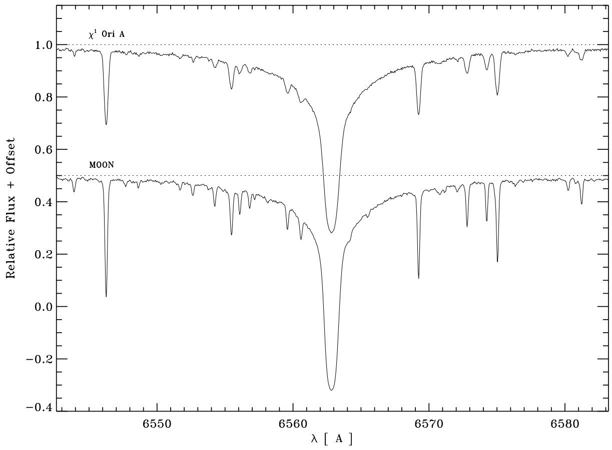

Fig. 2. A spectrum of χ^1 Ori A compared to the moon (=reflected sun light) in the range of H$_\alpha$ at 6563 Å. Note the considerable rotational velocity of χ^1 Ori A, $v \sin i = 8.7$ km s^{-1}, and the slightly filled-in line core of H$_\alpha$.

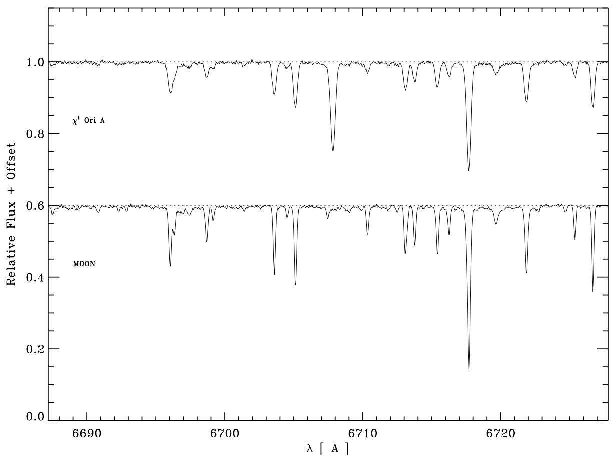

Fig. 3. Same as Fig. 2, but for the range of lithium at 6707.8 Å and calcium at 6717.8 Å.

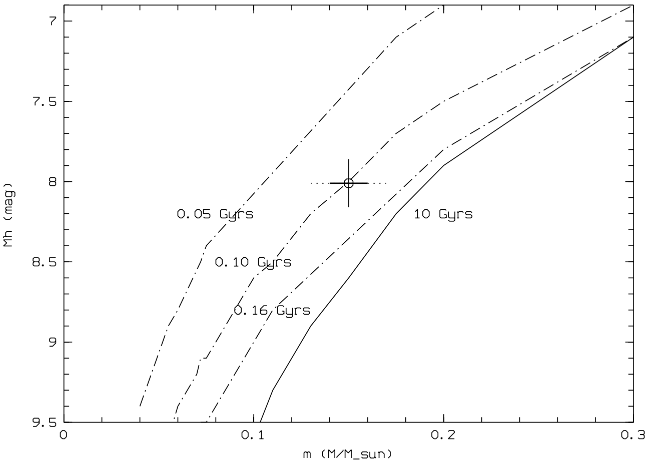

Fig. 4. Baraffe et al. (1998) isochrones for solar metallicity in a mass-luminosity plot compared to the position of χ^1 Ori B. The error-bars for the mass are derived by the spectroscopy (solid) and for the dynamical mass (dots). The age for χ^1 Ori B ranges from 70–130 Myrs using the dynamical mass.

5. Results and discussion

The mass of the companion to χ^1 Ori has been determined precisely to (0.15 ± 0.005) $M_{\chi^1\ \mathrm{Ori}}$ (Han & Gatewood 2002). The main uncertainty is $M_{\chi^1\ \mathrm{Ori}}$. This leads to a spectroscopic (0.15 ± 0.01 $M_\odot$) and dynamic mass (0.15 ± 0.02 $M_\odot$), which are both in good agreement.

The position of the χ^1 Ori B in the mass-luminosity plot (Figs. 4 and 5a) compared to the isochrones provided by Baraffe et al. (1998) indicates that the star lies about 0.50 ± 0.10 mag above the main sequence.

Figures 5b and 5c show H-R diagrams for the primary star including the tracks of Baraffe et al. (1998). Figure 5b shows models for [M/H] = 0, Y = 0.275, and the mixing length of $L_{\mathrm{mix}} = H_{\mathrm{P}}$. Baraffe et al. (1998) acknowledge that these models do not reproduce the sun at present age. Those tracks and isochrones also do not reproduce χ^1 Ori A.

Figure 5c shows the same as Fig. 5b except that the parameters [M/H] = 0, Y = 0.282, and the mixing length of $L_{\mathrm{mix}} = 1.9\,H_{\mathrm{P}}$ were adjusted to fit the sun. With these parameters the present sun could be reproduced and for χ^1 Ori A they also seem to work. The M_H predicted by Baraffe et al. (1998) is a bit lower than the measured M_H value for χ^1 Ori A. This could be because χ^1 Ori A is slightly iron underabundant ([Fe/H] = −0.07 ± 0.07) and the tracks were calculated for solar abundance. No tracks for masses of 0.15–0.175 $M_\odot$ are available for the model with the parameter set to fit the sun.

The age prediction by the pre-main-sequence models can be directly compared to other age determinations for the Ursa Major Cluster. While the canonical value for the age of the Ursa Major Cluster is 300 Myrs (cf. e.g. Soderblom & Mayor 1993, and references therein) derived by comparing the members of the Ursa Major Cluster nucleus stars in a color-magnitude diagram to theoretical isochrones computed by VandenBerg (1985), more recent observations of Sirius' white dwarf companion led Holberg et al. (1998) to suggest an age of 160 Myrs with reference to the cooling tracks of Wood (1992). Since Sirius B is also well-known as a fairly massive degenerate white dwarf with a mass of M = 1.034 ± 0.026 $M_\odot$ (Holberg et al. 1998), the initial-final mass relation suggests a progenitor of about 6–7 $M_\odot$ which means that we can expect

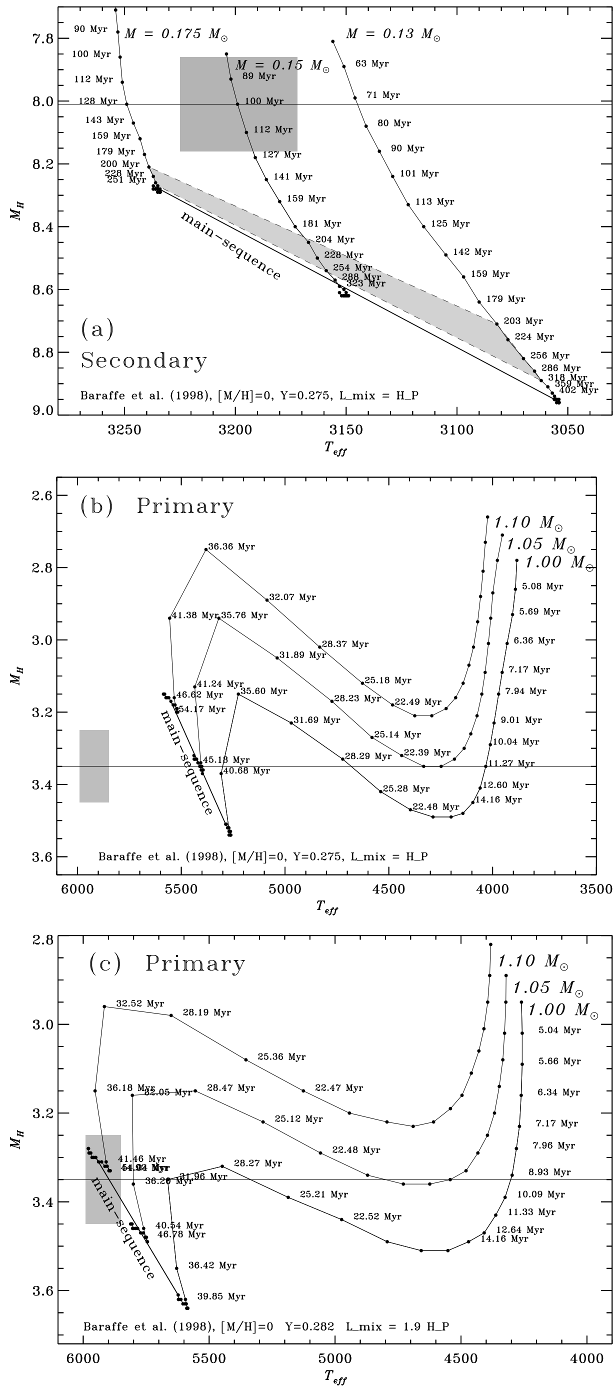

Fig. 5. Baraffe et al. (1998) tracks for solar metallicity. The horizontal line in the first plot gives M_{H} for the companion star with the top shaded area indication the 1σ error for M_{H} and the temperature range. In panel **a)**, the bottom shaded area is the age range determined for the Ursa Major cluster using different methods. With a mass of 0.15 $M_\odot$ the companion appears younger compared to the age range of the Ursa Major cluster. In the other two panels the same tracks plotted are for the primary, indicating the position of the primary by the shaded area. In panel **a)** and **b)** the model parameters are [M/H] = 0, Y = 0.275 and $L_{\mathrm{mix}} = H_{\mathrm{P}}$. For **c)** the parameters have been adjusted to fit the sun to [M/H] = 0, Y = 0.282 and $L_{\mathrm{mix}} = 1.9\,H_{\mathrm{P}}$.

another ~60–70 Myr for the pre-white-dwarf evolution. Hence, an age only somewhat above 200 Myrs may be more in line with this nearby open cluster. More recent white dwarf cooling models of Salaris et al. (2000) (models with a pure hydrogen atmosphere) suggest the age of the white dwarf of 111 Myrs derived from the V-magnitude and the temperature published by Holberg et al. (1998). Assuming the lifetime of the progenitor of the white dwarf of 46 Myrs this leads to an age of the UMa cluster of 157 Myrs.

The comparison of the age using Baraffe et al. (1998) (70–130 Myrs) to the ages of the Ursa Major Cluster (200–300 Myrs) indicate that either: (i) the Ursa Major Cluster has a larger than expected age spread, (ii) there are problems with the models at a solar and/or at ~0.15 $M_\odot$ mass, (iii) the canonical age for the Ursa Major Cluster is too high (300 Myrs), or (iv) χ^1 Ori is not a member of the Cluster. Considering possibility (i), we note that the age spread of 70–300 Myrs seems too large for a Cluster. As for the option (iv), χ^1 Ori is a classical member of the Ursa Major Cluster, located near the cluster center. The spectrum of χ^1 Ori A would support an age of 200 Myrs regarding the activity indicators, as would the cooling tracks for the Sirius B white dwarf.

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