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Letter to the Editor

Lithium-depleted stars in the young σ Orionis cluster*

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ABSTRACT

Context. Knowledge of the age distribution of stars in young clusters and associations is crucial to constrain models of star formation. HR diagrams of different young clusters and associations suggest the presence of age spreads, but the influence of errors on the derived ages is still largely debated. Determination of lithium abundances in low-mass stars represents an alternative and robust way to infer stellar ages.

Aims. We measured lithium in a sample of low mass members of the young (4–5 Myr) σ Ori cluster with the main goal of investigating its star formation history.

Methods. Using the FLAMES multi-object spectrograph on VLT/UT2, we obtained spectra of 98 candidate cluster members. The spectra were used to determine radial velocities, to infer the presence of Hα emission, and to measure the strength of the Li I 670.8 nm absorption line.

Results. Using radial velocities, Hα and Li, together with information on X-ray emission, we identified 59 high probability cluster members. Three of them show severe Li depletion. The nuclear ages inferred for these highly depleted stars exceed 10–15 Myr; for two of them these values are in good agreement with the isochronal age, while for the third star the nuclear age exceeds the isochronal one.

Key words. stars: pre-main sequence – Galaxy: open clusters and associations: individual: σ Orionis – stars: abundances – stars: low-mass, brown dwarfs

1. Introduction

The timescale of stellar birth within molecular clouds is one of the main open issues in star formation theory. Two scenarios have been proposed to explain the observational results: rapid star formation (RSF) or slow accelerating star formation (SASF) (Elmegreen 2000; Palla & Stahler 2002). HR diagrams, which are the main tool to determine Pre-Main Sequence (PMS) stellar ages, show a spread of $\gtrsim 10^7$ years in individual clusters and associations, supporting the SASF model, but the effect of various sources of errors, both observational and theoretical, is largely debated (Hartmann 2001; Burningham et al. 2005). Lithium (Li) abundances can be used as an independent and robust method to determine ages of young objects (Martín 1998a,b), since low-mass stars in the range 0.5–0.08 $M_\odot$ deplete their initial Li content during the PMS phase (Bodenheimer 1965; Baraffe et al. 1998). The timescale of Li depletion depends on mass, with higher mass stars (0.5–0.3 $M_\odot$) starting to burn it after 5–10 Myr and lower mass stars ($M < 0.2\ M_\odot$) after 20–30 Myr. (Palla et al. 2005) employed the Li age-dating method among low-mass members of the Orion Nebula Cluster and found four Li-depleted stars with nuclear ages ~10 Myr.

The σ Ori cluster was discovered by ROSAT (Walter et al. 1997) around the O9.5 V binary star σ Ori AB (distance 350^{+166}_{-85} pc, Perryman et al. 1997). Its low-mass stellar population has been intensively studied by photometry and low-resolution spectroscopy in the optical and near-infrared (Zapatero Osorio et al. 2002; Barrado y Navascués et al. 2003; Sherry et al. 2004; Scholz & Eislöffel 2004; Oliveira et al. 2004), while the X-ray properties have been investigated most recently by (2006) using XMM-Newton. Oliveira et al. (2002) determined its isochronal median age to be $4.2^{+2.7}_{-1.5}$ Myr. Subsequently, Oliveira et al. 2004 presented evidence for a large age spread (~30 Myr) in the $I/I - J$ Color–Magnitude Diagram (CMD), and suggested that part of it could be due to photometric variability of the PMS stars. Kenyon et al. (2005) have found bona fide cluster members with small Li line equivalent widths (*EW*), possibly indicating a certain amount of depletion. Finally, Jeffries et al. (2006) have discovered two kinematically separate populations of young PMS stars, one concentrated around σ Ori AB, sharing a common radial velocity with this star ($v_1 = 31.0 \pm 0.5$ km s^{-1}), and the second one, more dispersed in the sky, with a radial velocity similar to that of the Orion OB1a and 1b associations ($v_2 = 23.8 \pm 1.1$ km s^{-1}). In this Letter, we report on the discovery of three high-probability members of the main σ Ori cluster with Li abundances of a factor of about 1000 below the interstellar value. This result was obtained as part of a VLT/FLAMES survey to study membership, Li abundances, and accretion

* Based on data collected at the ESO Very Large Telescope, Paranal Observatory, Chile [program 074.D-0136(A)].

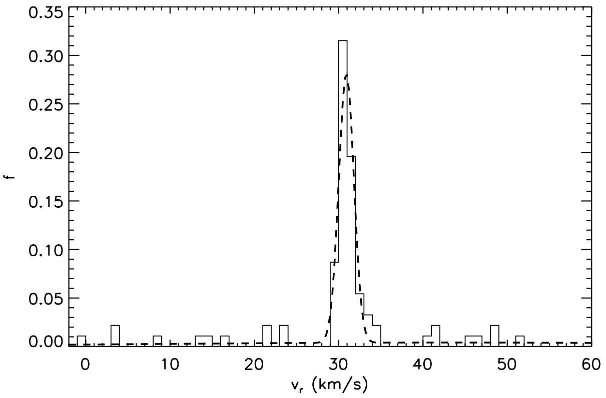

Fig. 1. Observed RV distribution of all the stars of the sample, with the curve resulting from the fitting with the sum of two Gaussians overplotted (dashed line).

diagnostics of a large sample of K and M stars around σ Ori AB (Sacco et al., in preparation).

2. Observations and results

2.1. Target selection and observations

We have selected 98 cluster candidates from previous studies. To secure a high fraction of cluster members, we have granted higher priority to stars detected in X-rays by Franciosini et al. (2006) and with isochronal ages $\lesssim$10 Myr from optical and infrared CMDs. All stars of the sample have an infrared counterpart in the 2MASS catalog (Skrutskie et al. 2006), while for 79 of them optical photometry is available in the literature (Wolk 1996; Zapatero Osorio et al. 2002; 2003; Burningham et al. 2005; Kenyon et al. 2005). The sample stars were observed using FLAMES on VLT/UT2 (Pasquini et al. 2002). FLAMES was operated in MEDUSA mode with the high resolution ($\lambda/\Delta\lambda$ = 17 000) HR15N grating covering the spectral range 647–679 nm. The Field of View (FoV) was centered at RA = $05^h38^m48\overset{s}{.}9$ and Dec = $-02^d34^m22^s$ and is almost coincident with the FoV of XMM-Newton (2006). The observations were divided in six runs between October and December 2004, for a total exposure time on target of 4.3 h. Data reduction was performed using the GIRAFFE girBLDRS pipeline 1.12, following the standard steps Blecha & Simond (2004). Sky subtraction was performed separately using an average of six-seven sky spectra.

2.2. Membership

We have measured radial velocities (RVs) using the IRAF[1] task FXCOR by Fourier cross-correlation with two template spectra chosen from among sample stars with no accretion signatures. For 86 stars we derived a median RV as the weighted average of the six values measured for the different runs, while the remaining 12 stars turned out to be candidate binaries and will be discussed in the forthcoming paper. The cluster RV was determined by fitting the observed RV distribution, shown in Fig. 1, with the weighted sum of 2 Gaussian distributions, one for the cluster and the other for the field. The best fit yields a value of $v_C = 30.91 \pm 0.90$ km s^{-1} for the cluster and $v_F = 43 \pm 36$ km s^{-1} for the field. Our cluster velocity is in excellent agreement with that ($v_C = 31.0 \pm 0.5$ km s^{-1}) determined by Jeffries et al. (2006).

We considered stars with RVs within 3σ from the average as cluster members, yielding 61 members and 25 field stars. The statistical contamination of the cluster member sample, estimated by integrating the field star distribution between $v_C - 3\sigma_C$ and $v_C + 3\sigma_C$, is ~2 stars. The second requirement on membership is the presence of Hα in emission. Among the 25 RV non-members, 24 are also field stars according to Hα, while one star, which appears young based on Hα, has a radial velocity (v = 23.73 $\pm$ 0.45 km s^{-1}) similar to that of the second population discovered by Jeffries et al. (2006). Note that all the non-members have Li I 670.8 nm pseudo equivalent width (pEW) smaller than 200 mÅ. Finally, among the 61 RV cluster members, 56 are also PMS stars from Hα emission and from the strength of the Li line; two stars with Hα in absorption and no Li are most likely field stars.

The remaining 3 RV cluster members, listed in Table 1, have Hα in emission and Li pEW less than 200 mÅ. As shown in Fig. 2, the Li line is clearly identified (EW = 150 mÅ) in the spectrum of SE51, but not in those of SWW127 and J053914.5-022834. These stars have an X-ray counterpart and are determinated to be PMS stars in CMDs. Moreover, J053914.5-022834 shows excess in K–L (Oliveira et al. 2004), and SE51 is characterized by photometric variability (Scholz & Eislöffel 2004). Considering that only two out of 22 field stars in our sample have an X-ray counterpart (2 field stars are out of the XMM FoV) and that the probability of having a field star with RV between $v_C - 3\sigma_C$ and $v_C + 3\sigma_C$ is 0.056, the probability of finding, among the RV cluster members, 3 field stars with an X-ray counterpart is less than 5×10^{-3}. We conclude that, although physical membership must be confirmed by, e.g., proper motion studies, we regard as unlikely that all of them are non members.

Table 1. Membership indicators of Li-depleted stars.

Object[a]	v_r (km s^{-1})	Hα EW (Å)	Log L_X (erg/s)	PMS indicator
SE51[b]	29.5 ± 0.5	−1.1	29.22	variable
SWW127[c]	33.2 ± 0.5	−2.6	29.51	–
J053914.5-022834[d]	29.2 ± 0.5	−4.6	30.17	NIR ex.

[a] See (2006); [b] (Scholz & Eislöffel 2004); [c] (Sherry et al. 2004).

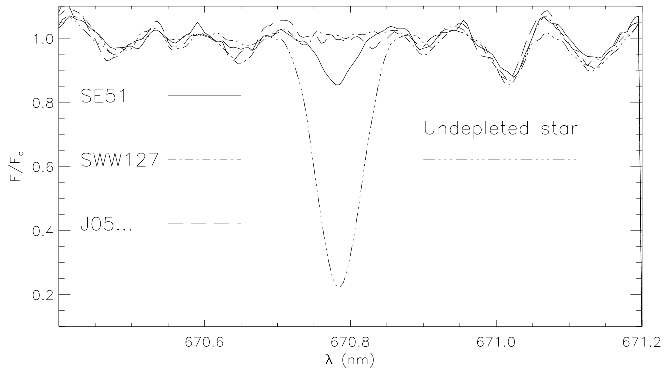

Fig. 2. Spectra of the three Li-depleted stars listed in Table 1; namely, SWW127 (dotted line), J053914.5-022834 (dashed line), and SE51 (continuous line). For comparison the spectrum of an undepleted star in same temperature range of those reported in Table 2 is also shown (dotted-dashed line).

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for research in Astronomy, Inc., under contract to the National Science Foundation.

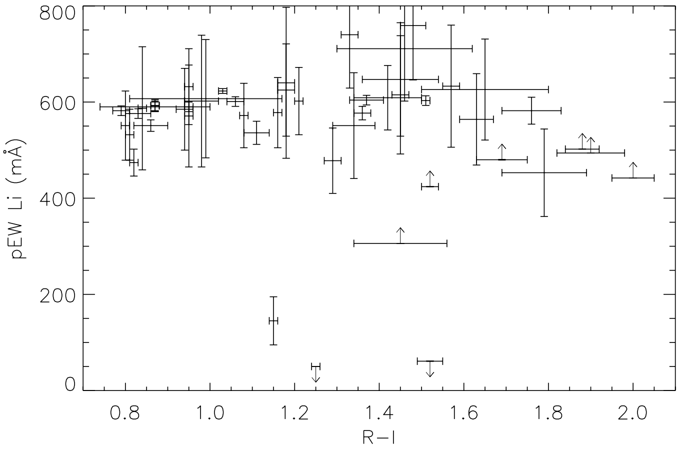

Fig. 3. pEWs of the Li line corrected for veiling as a function of $R-I$ color for cluster members with available optical photometry. Upward and downward arrows denote lower and upper limits.

2.3. Lithium-depleted stars

pEWs of the Li line were measured using the IRAF task SPLOT, by direct integration of the line profile over an interval of 0.2 nm. Measured pEWs may be affected by spectral veiling. We have estimated r, the ratio of the excess emission to the photospheric continuum, for all stars of the sample from the measurement of the EWs of three absorption lines (V I 662.5 nm, Ni I 664.3 nm, Fe I 666.3 nm) in their spectra and in those of 11 unveiled comparison stars with similar temperatures (see Palla et al. 2005). In those cases where we were not able to measure at least 2 lines, because of low S/N or high veiling, we have considered r indeterminate and the measured Li pEWs are lower limits to the true values. Derived r values range between 0 and 1.4, with errors of about 0.1–0.2. Figure 3 shows pEWs of the Li line, corrected for veiling, for stars with available optical photometry. The median pEW is 590 mÅ, with a typical dispersion of ~100 mÅ. The scatter in Li pEWs could be due to measurement errors, but we cannot exclude the presence of some partially depleted stars. The three stars reported in Table 1 are not veiled (r = 0.0–0.2) and their Li pEWs are less than 200 mÅ, indicating a large amount of Li depletion.

We have determined Li abundances for these three stars using curves of growth of Palla et al. (2006), based on Pavlenko (2001) models and spectral code. Surface gravity was fixed at $\log g$ = 4.0 dex, the expected value for a 4 Myr old late-type star by Baraffe et al. (1998) models. The effective temperature of the depleted stars is given in Table 2: in the case of J053914.5-022834 it has been derived from the spectral type measured by (Zapatero Osorio et al. 2002), while $T_{\rm eff}$ of SE51 and SWW127 are estimated from the color indexes $R-I$ and $I-J$, using the models of (Baraffe et al. 1998). The resulting Li abundances are listed in Table 2 and are a factor of $\gtrsim$1000 below the interstellar value (A(Li) = 3.3). We stress that even relatively large errors in $T_{\rm eff}$ and/or $\log g$ would not greatly affect Li abundances (or depletion factors), given the extremely small pEWs (or upper limits to pEWs). Similarly, the low abundances cannot be explained by veiling, since it would imply a value of $r \gg 1$, or by other sources of error, such as uncertainty in the pseudo-continuum. Contrary to the suggestion of (Kenyon et al. 2005), we believe that the measured low pEWs represent real Li depletion, since Pavlenko (2001) models provide a correct treatment of the Li line formation in cool objects and pEWs below ~170 mÅ imply that only TiO contributes to the 670.8 feature.

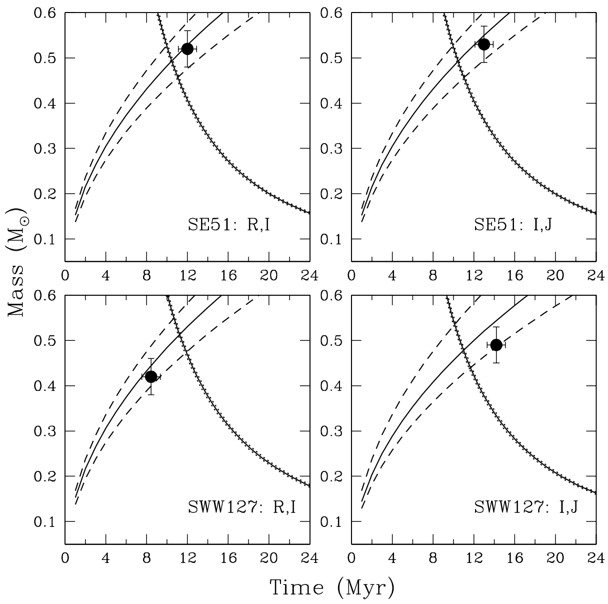

Fig. 4. Mass vs. age plot for the Li-depleted stars SE51 and SWW127. $T_{\rm eff}$ and bolometric correction have been derived using the color indices $R-I$ (left-hand panels) and $I-J$ (right-hand panels) and the models of Baraffe et al. (1998). Continuous curves represent the locus of constant luminosity (positive slope) and constant Li abundance (negative slope), while dashed curves indicate the uncertainty range. The circles with the error bars give the masses and ages computed from models of Palla & Stahler (1999).

3. Discussion and conclusion

The three Li-depleted, high probability members of the σ Ori cluster represent an example of post T Tauri stars (following the definition of Martín 1997), and allow us to investigate its star formation history from a novel point of view. Isochronal and nuclear ages ($t_{\rm HRD}$) and masses ($M_{\rm HRD}$) for the three Li-depleted stars are listed Table 2. These values have been derived from the models of Palla & Stahler (1999) using the $T_{\rm eff}$ and luminosity range given in the table. In the last two columns we list the nuclear mass ($M_{\rm Li}$) and age ($t_{\rm Li}$) estimated following (Palla et al. 2005), based on (Bildsten et al. 1997). The latter provides analytical prescriptions to derive the age vs. stellar luminosity and the age vs. Li abundance relations for a fully convective star undergoing gravitational contraction at a nearly constant $T_{\rm eff}$ and assuming fast and complete mixing. In Fig. 4 we display the mass vs. age relations at fixed luminosity (positive slope) and Li abundance (negative slope) predicted by the models. The intersection of the two curves gives the mass and nuclear age of the star.

We find that the age and mass of SE51 and SWW127 derived from Li are in very good agreement with the isochronal values obtained using both $R-I$ and $I-J$ colors. On the contrary, the measured amount of Li depletion for J053914.5-022834 is too large for the isochronal age and low mass from evolutionary tracks.

Considering that most of the remaining stars of our sample have pEWs consistent with the interstellar value, our results support the view that the bulk of the σOri population has an age $\lesssim$4–6 Myr. However, three low-mass, high probability members are definitively older than ~10 Myr. Therefore, we propose that σOri has been forming stars on a timescale of >10–15 Myr, as found in the case of the Orion Nebula Cluster.

Table 2. Li depleted stars and their properties.

Object	$T_{\rm eff}$ (K) (R, I/I, J)	Log ($L/L_{\odot}$) (R, I/I, J)	Li EW (mÅ)	A(Li)	$M_{\rm HRD}$ ($M_{\odot}$)	$t_{\rm HRD}$ (Myr)	$M_{\rm Li}$ ($M_{\odot}$)	$t_{\rm Li}$ (Myr)
SE51	3750 ± 20/3750 ± 60	−0.91 ± 0.01/−0.91 ± 0.02	150 ± 50	−0.5 ± 0.5	0.52–0.53	12–13	0.49 ± 0.04	10.5 ± 0.6
SWW127	3645 ± 15/3720 ± 60	−0.92 ± 0.01/−0.94 ± 0.02	<90	<−1.0	0.42–0.49	8.4–14.2	≥0.44	≥10
J053914.5-022834	3345 ± 70	−1.14 ± 0.06	<100	<−0.7	0.23 ± 0.05	4.5 ± 1.5	≥0.4	≥15

Finally, we note that our sample has been selected requiring an isochronal age from CMDs less than ~10 Myr. This bias has precluded the identification of additional Li-depleted, old stars that might exist in the σ Ori cluster. Further observations at low spectral resolution to derive stellar parameters, as well as at high resolution to measure lithium abundances on a larger sample of stars, can help to fully characterize the star formation history of the cluster.

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