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On the nature of the ROSAT X-ray selected weak-line T Tauri stars in Orion

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Abstract. We analyse the nature of the *ROSAT* all-sky survey (RASS) X-ray sources in the direction of Orion identified with stars showing the Li I λ 6708 Å line strong in absorption and hence classified as weak-line T Tauri stars (WTTS) in a previous study. The stars are found to be widely spread throughout the entire studied area of $\approx$ 450 squared degrees. We discuss the broad-band UBVRI$_{KC}$ JHKL and narrow-band $uvby$-β photometry as well as the spectroscopy of these stars. From the broad-band photometry and spectroscopy we derive the stellar parameters assuming that all stars are located at 460 pc and are physically associated with the Orion star forming region (SFR). By comparison with theoretical pre-main sequence (PMS) evolutionary tracks, all stars can be classified as WTTS with masses raging from 0.8M$_\odot$ to about 3.4M$_\odot$ and ages from 2×10^5yr to 7×10^6yr. We do not find any correlation between the spatial distribution and age or any other stellar parameter if the above distance for all the stars is assumed. We do find, however, that the stars with higher Li I (λ 6708 Å) line strength tend to concentrate toward the molecular clouds. From the analysis of the $uvby$-β photometric data we find that part of a subsample of the RASS lithium stars are foreground young stars not associated with Orion. We conclude that the sample of lithium RASS stars in Orion is an admixture of different populations of stars located at different distances, namely: true Orion WTTS and a population of foreground and yet young stars. The latter could be associated with the Gould Belt or may be pleiades-age stars.

Key words: stars: pre-main-sequence; formation; fundamental parameters – X-ray: stars – ISM: Orion clouds

1. Introduction

X-ray surveys with the *Einstein* and *ROSAT* satellites have been very successful on finding a large number of low-mass (M $\leq$ 3 M$_\odot$) X-ray emitting young stars in the general vicinity of star forming regions (SFRs) (Walter et al. 1988; Krautter et al. 1994, 1996; and references therein). Most of these stars exhibit weak emission in Hα (W(Hα) $\leq$ 10 Å) or no emission lines in their spectra and lack ultraviolet (UV) or infrared (IR) excesses in their spectral energy distributions (SEDs), features that characterize the more active line emission of Classical T Tauri stars (CTTS). The young nature of the X-ray selected weak-line emission stars is assessed by the presence of the strong lithium (λ6708 Å) absorption line, comparable in strength to that of CTTS. Lithium is rapidly destroyed in the deeper convective layers of low-mass stars in the early phases of the stellar evolution (Bodenheimer 1965). Because of the morphologic similarities with the more conspicuous CTTS, these X-ray emitting stars have been coined as weak-line T Tauri stars. While practically all the CTTS are found next to the denser clumps of molecular clouds, the majority of the X-ray emitting weak-line T Tauri stars (WTTS) identified on the basis of the *ROSAT* all-sky survey (RASS) have been found widely spread in SFRs (Alcalá et al. 1995, Wichmann et al. 1996, Krautter et al. 1997, Kunkel 1996). The origin of the wide spread distribution of the WTTS is not yet clear. If all pre-main sequence (PMS) stars next to the denser parts of the molecular cloud formed within a gravitative contraction time, then the outermost stars should be the oldermost ones. But observations show that some of these stars had not enough time to diffuse to their far position within a characteristic time given by the velocity dispersion and space location of the stars.

In a recent study we have identified 112 new stars with lithium in the direction of the Orion complex on the basis of the RASS and follow–up ground–based spectroscopic and photometric observations (Alcalá et al. 1996, henceforth A96). On the basis of the chromospheric activity and the strength of the lithium line λ6708 Å, these stars were classified as new Orion WTTS by Alcalá et al. (A96). Because of the high number of X-ray sources detected by the RASS in Orion (Sterzik et al. 1995), the optical identification of the RASS sources in the region is far from complete. Nevertheless, the kindness of the data presented

Send offprint requests to: J.M. Alcalá by A96 resides in the fact that the sample is representative of the RASS toward Orion and that this SFR is at a larger distance (by a factor of about 3) than other well–studied SFRs like Taurus, Chamaeleon and Lupus giving the possibility to trace X-ray emitting young stars in a larger volume along the line of sight.

In this paper, we analyse the spectroscopic and photometric data of more than 60% of the sample of stars presented in A96. In Sect. 2 we describe the sample and its data base. Assuming a 460 pc narrow distance distribution and using the spectroscopy and broad–band photometry by A96, we derive and discuss the stellar parameters in Sect. 3. In Sect. 4 we use the narrow–band Strömgren photometry to derive distance independent stellar parameters for a subsample of stars. We discuss our results in Sect. 5 and present our conclusions in Sect. 6.

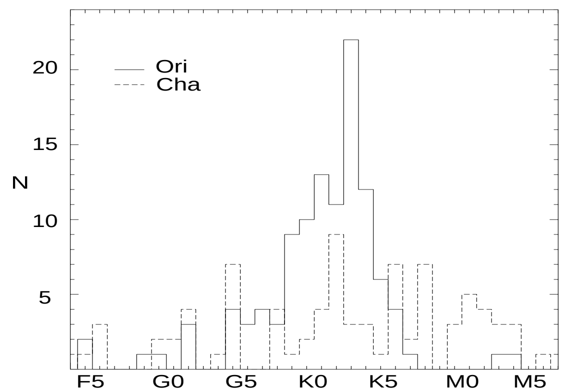

Fig. 1. Spectral type distribution of the 112 new WTTS found in the direction of Orion. The spectral type distribution of the WTTS in Chamaeleon by Alcalá et al. (1995) (dotted line) is also shown.

2. The sample and the database

Spectroscopic data for 112 WTTS in the direction of Orion are presented in A96. Of these, 78 have $UBV(RI)_{\rm KC}$ $JHKL$ and $uvby$-β photometry and constitute our primary data base for the investigations described here. The photometry in the different systems was not acquired simultaneously but in different epochs. Despite of this, WTTS are expected to be mild variables and our results will not suffer a significant change because of this. The available photometric data are divided as follows: 39, 45 and 42 stars in our sample have $UBV(RI)_{\rm KC}$ $JHKL$ and $uvby$-β photometry respectively; 16 stars have both $UBV(RI)_{\rm KC}$ and $JHKL$ photometry. Of these, 14 have $uvby$-β photometry too. 9 of the 23 stars that have UBV(RI)$_{KC}$ also have uvby-β photometry and 8 of the 29 stars with only $JHKL$, have $uvby$-β photometry. 11 stars in the sample have $uvby$-β photometry only. These data allow the determination of the stellar parameters for about 60% of the entire sample of the stars presented in A96 and hence to carry out a statistical analysis of their properties, comparing them with the other well known low-mass PMS stars. We make the reader aware that the errors for the $uvby$-β photometry quoted in A96 are too high: from a reinspection of the data and its reduction (i.e. shot noise statistics and transformation residuals of the reference stars), we estimate the typical uncertainties to be $0.^m03$, 0.01, 0.02, 0.02, 0.015 in V, b-y, $[m_1]$, $[c_1]$ and β, respectively.

2.1. Distribution of spectral types

In Fig. 1 we depict the spectral type distribution (STD) of the stars reported in A96. The peak of the distribution is at about K4. The STD of the WTTS in the Chamaeleon (Cha) SFR given by Alcalá et al. (1995) is overplotted for comparison. The lack of late type stars in our sample as compared to the Cha stars can be attributed to a selection effect due to the limiting flux of the RASS: the exposure times near the celestial pole are a factor of about three longer than for X-ray sources near the celestial equator.

2.2. Apparent magnitude distribution

In Fig. 2 we compare the apparent-magnitude frequency distributions of the WTTS in Orion and Chamaeleon, where the data of the latter were taken from Alcalá et al. (1995). From the comparison, we see that the Orion WTTS distribution is reclined towards more luminous stars, indicating that the fainter and thus later spectral type stars were missed in our sample (cf. Fig. 2a). If we restrict Chamaeleon's sample to have the same range of spectral types, from G5 to K5, given by most of the Orion's WTTS reported here, surprisingly, both distributions look alike (cf. Fig. 2b). One expects Orion's distribution to be leaned to fainter stars because of the distance modulus differences. In Fig. 2b we also show Orion's CTTS constrained to the same spectral types as our sample of WTTS. The CTTS were taken from the Herbig & Bell catalog (1988). Note that the CTTS peak at about 14^m, as expected, and our sample have their maximum at about $11.^m5$, (see Fig. 2b). From Fig. 2b one also sees that Orion's WTTS are as bright as those WTTS in Chamaeleon, a SFR with a much shorter distance ($\approx$ 150 pc, Schwartz 1988). Consequently, if the stars are physically associated with the SFR, then Orion's WTTS are significantly younger or more massive than their (equal spectral type) counterparts in Chamaeleon.

2.3. Broad-band colors and IS extinction of the program stars

We derredened the broad band photometry using the mean IS extinction curve by Mathis (1990). The intrinsic colors vs. spectral type relation for ZAMS stars by Bessell & Brett (1988) was used to estimate intrinsic colors of the sample stars. The relations given by Taylor (1986) were applied to transform magnitudes and colors from the Kron-Cousins to the Johnson's system and the relation given in Terranegra et al. (1994, hereafter TCDG94) was used to transform the (B-V) colors to the (b-y) system. Note that the transformation uncertainties are negligible for the present purposes of the discussion because of the absence of any strong features in their SEDs of the WTTS. With the exception of a few objects (see below), all program stars are affected by

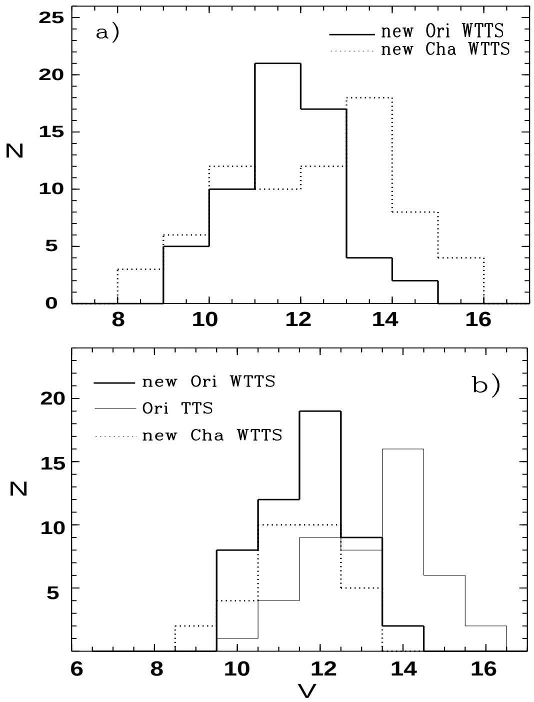

Fig. 2a and b. Frequency distribution of V magnitude for TTS in Orion and Chamaeleon. In the upper panel the V magnitude distribution of the WTTS in Orion is compared with that of the WTTS sample in Chamaeleon by Alcalá et al. (1995). In the lower panel the V magnitude distributions of the new WTTS in Orion is compared with that of Orion TTS and new Cha WTTS, but the three samples are restricted to the same range of spectral types from G5 to K5, see text for details.

moderate IS extinction ($A_V \leq 1.6$, i.e. the amount typically observed from here to the front of Orion's SFR). The location of the sample stars in the (B-V,V-I) and (J-H,H-K) diagrams (cf. Fig. 3 here and Fig. 5 of A96) are in good agreement with this.

0535.0-0411 has moderate near IR flux excess suggesting a warm CS dust envelope or disk. 0532.6-0522 (HR Ori) and 0535.3-0059 have a too red (V-I) color for their (B-V) color. HR Ori, together with 0535.3-0059 have the weakest B flux of the sample and therefore the largest Schott noise at this passband of the sample, making their B magnitude more uncertain and hence their present position in the two color diagram unreliable. On the other hand, the (b-y) color of the two stars are normal, giving support to this explanation. The too blue (B-V) color of 0534.7-0423 for a K star is most probably due to a misidentification with the southern (brighter) neighbor star (see finding chart in A96), since this star has normal magnitude and colors for its spectral type in the Strömgren system. We can conclude that the majority of the new WTTS in Orion have normal colors and hence suffer of little or no masking effects. Consequently, we can use confidently bolometric corrections to estimate stellar luminosities.

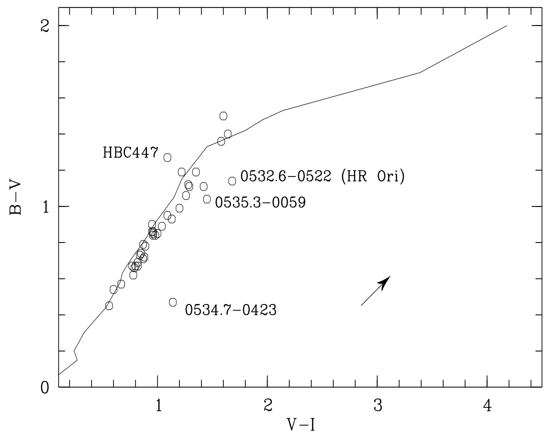

Fig. 3. Color-color diagram of the new WTTS. The solid line represents the intrinsic colors of dwarfs from Bessel and Brett (1988). The A_V = 0.5 reddening vector is also plotted.

2.4. Color-magnitude (CM) diagrams and the new WTTS

From the data given in Tables 5 and 6 of A96, we have constructed the CM diagrams (V,V-I), (V,b-y) and (K,H-K) of the program stars. Note that as long as no abnormal strong stellar spectral features are present within the filter passband, we can intercompare the two sets of optical (broad and medium band photometric) data using a linear transformation of the color term (e.g. TCDG94), since the visual magnitudes in the two photometric systems are referred to Johnson's V magnitudes. If we compared the location of the new WTTS in the (optical) CM diagram with that of CTTS associated with Orion's SFR (e.g. TCDG94), it results that they are indistinguishable. Hence one should expect very similar stellar parameters and evolutionary stages for the two types of stars. In Fig. 4 we display the location in the V-(b-y) plane of all the WTTS of our sample that have Strömgren (filled circles) or Johnson (open circles) photometry transformed to the Strömgren's system using the linear relation given in TCDG94. The $3.^m5$ dispersion in the V filter outstands in Fig. 4.

The data of the new WTTS are compatible with another and yet very interesting interpretation: assuming that the WTTS sample in Orion are young dwarfs and that the spread of their loci in the CM diagram is due primarily to distance differences and not to evolutionary effects of the individual objects, we find a reasonable fit of the ZAMS to the data yielding an (upper bound) estimate for the distance of 300 $\pm$ 20 pc (the reddening of the program stars was assumed negligible, see Sect. 2.3). From the main sequence (MS) spread we also find a (lower bound) distance estimate of 80 $\pm$ 20 pc (cf. Fig. 4). These distance bounds are in good agreement with the low IS extinction observed towards a significant fraction of the program stars. This new "foreground star" possibility will be explored further on. First we assume a 460 pc narrow distance distribution for the new WTTS and derive their properties.

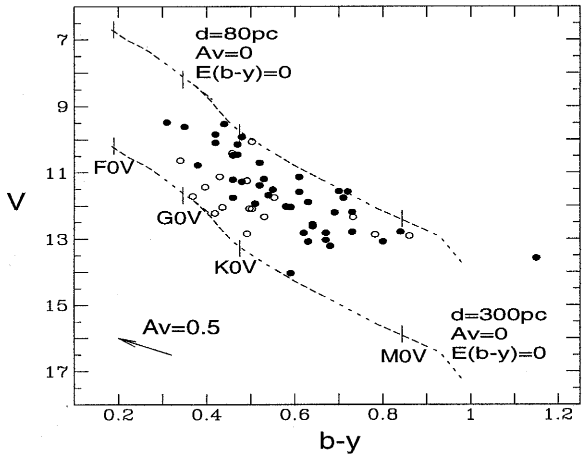

Fig. 4. V–(b-y) diagram of new WTTS of our sample with Strömgren (filled circles) or Johnson (open circles) photometry transformed to the Strömgren's system. The two dashed lines represent the position of the free-reddening "apparent" ZAMS placed at 80 and 300 pc.

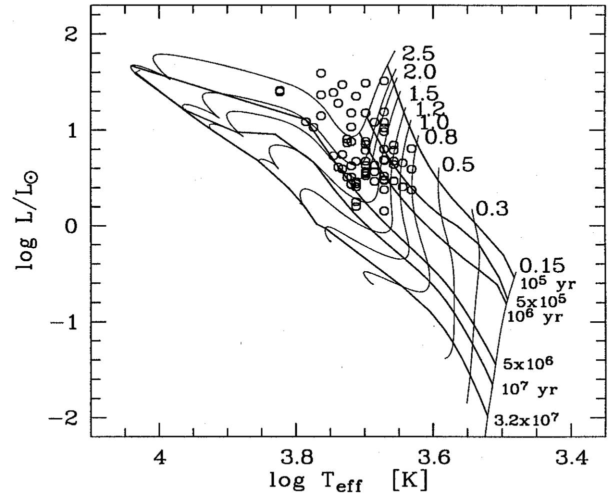

Fig. 5. H-R diagram of the new Li rich stars in the direction of Orion. The PMS evolutionary tracks are from the third set by D'Antona and Mazzitelli (1994). The isochrones are plotted as thicker lines. See text for details.

3. Stellar parameters from the spectroscopy and the broad-band photometry

In this section we derive the stellar parameters for our sample using the spectral types and the broad-band photometric data reported in A96 and adopting the distance of 460 pc. A table with the derived stellar paramaters is available under request to the authors.

3.1. Stellar effective temperatures

The values of $log\,T_{eff}$ were estimated from the observed spectral types reported in A96 and using the relationship between spectral type and effective temperature for luminosity class V, given by de Jager and Nieuwenhijzen (1987). Since the accuracy of the spectral types is about ± 1 subclass in most cases, the corresponding uncertainty in $logT_{eff}$ is about ± 0.02 dex for stars with spectral types later than G0.

3.2. Stellar luminosities

The luminosities of the 68 stars with optical and near-IR photometry were computed in three ways: 1) For the 16 stars with both $UBV(RI)_{\rm KC}$ and near-IR photometry, the luminosities were derived by integrating the derredened SEDs. An integration of the SED for stars without any *JHK* photometry was not performed. 2) The $I_{\rm KC}$ magnitude corrected for interstellar extinction was used to obtain the bolometric luminosity (L_{BC}) by adopting a bolometric correction appropriate to a main–sequence star of the same spectral type. The relations given by Bessel and Wood (1984) were used to derive bolometric corrections. 3) The K magnitudes corrected for IS extinction were used to estimate bolometric luminosities of the program stars. The three methods yield internally consistent results. The typical errors in $logL_{bol}$ are estimated to be less than about 0.07 dex. However, larger systematic errors may be present because unresolved binaries.

For the rest of this section we use preferentially bolometric luminosities derived from the UBV(RI)$_{KC}$ or JHK data, in that order.

3.3. The H-R diagram

In Fig. 5 the locations of Orion's new WTTS in the HR-diagram are shown. On this diagram, the (third set of) PMS evolutionary tracks by D'Antona and Mazzitelli (1994, DM94) is overplotted. This set of PMS tracks was derived using Alexander et al. (1989) opacities and the mixing length theory (see DM94). It results that the new WTTS have masses and ages in the ranges $0.8M_{\odot} \leq M_{star} \leq 3.4M_{\odot}$ and $2\times10^5 yr \leq \tau_{age} \leq 7\times10^6 yr$, respectively. Thus, these objects can be classified as WTTS if they are indeed at a distance of 460 pc.

Noteworthy is the lack of stars with masses less than $0.8M_{\odot}$. This can be attributed to the limited sensitivity of the *ROSAT* all-sky survey and the distance to Orion's SFR.

In this narrow distance distribution approximation we do not find any correlation between the spatial distribution of the stars and their age or any other stellar parameters. There are very young (few 10^5 yr) stars located far from the molecular clouds and vice-versa. The presence of these very young WTTS far off the dense molecular clouds cannot be explained in terms of the canonical velocity dispersion of $\approx$ 1-2 km/s measured in the generality of SFRs (e.g. Jones & Herbig 1979).

Stellar properties inferred from the location of the stars in the HR-diagram are strongly affected by the uncertainty in the distance. In the next section an attempt is made to derive distance independent stellar aprameters for the subsample of stars with Strömgren photometry.

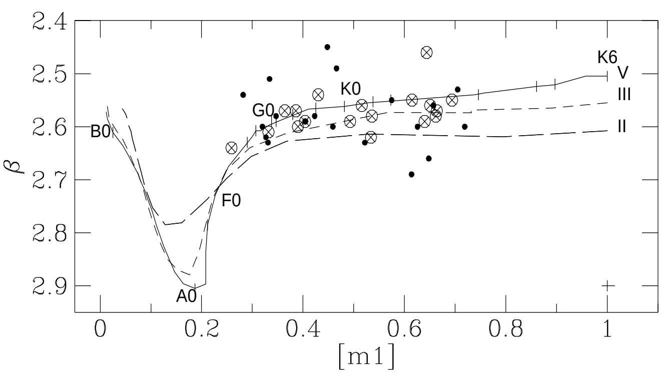

Fig. 6. $(\beta, [m_1])$ diagram of the new WTTS with Strömgren photometry.

4. Analysis from the Strömgren photometry

The *uvby*-β photometric system has since long proven to be a powerful tool for determining accurate physical parameters of stars. The four-color *uvby* photometry, supplemented with Hβ photometry, has been calibrated empirically in terms of absolute magnitudes and intrinsic colors for B, A, F and early G stars by Strömgren (1966) and Crawford (1975). More recently, the system has been extended to (mainly luminosity class V and IV) G, K and M stars in the general vicinity of the Sun by Olsen (1984). The correlations between MK spectral types, metallicity, stellar luminosity and the *uvby*-β photometry are clearly outlined in the (b-y)$_o$-c$_1$, (b-y)$_o$-m$_1$, [m$_1$]-[c$_1$] and the $(\beta, [m_1])$ diagrams (Olsen 1984 and references therein; TCDG94). In this section we will analyze the most important color-color diagrams in the *uvby*-β photometric system for our program stars.

4.1. The $(\beta, [m_1])$ diagram and the WTTS

The $(\beta, [m_1])$ diagram of a large sample of PMS stars is discussed by TCDG94. They find that the diagram is, in general, sensitive to T_{eff}, Hβ emission/absorption and to the surface gravity and hence stellar luminosity, particularly for the late type stars. A strong stellar mass in- or outflow would also give high β indices (cf. TCDG94). In Fig. 6 we show the location of Orion's WTTS in the $(\beta, [m_1])$ diagram. From a comparison of this figure with the equivalent figure for young emission-line stars of the Orion population by TCDG94, the difference is apparent: contrary to CTTS which have low β indices (which indicates Hβ in emission), the WTTS have a β index comparable to that of MS counterparts of the same spectral type, but usually higher.

In Fig. 6 we also show the loci of isogravity contours $log g$ = 4.0, 3.0 and 2.0 given by the models with [Fe/H]= 0.0 dex by Lester et al. (1986, [m$_1$]$\leq$ 0.3) and the empirical isoluminosity classes V, III and II constructed from the catalogue by Olsen (1984, [m$_1$]$>$ 0.3). Note the good match between the isogravity contours $log\ g$ = 2, 3 and 4 with the isoluminosity classes II, III and V, respectively. This behavior of the β-index for late type stars suggests that, besides the Balmer Hβ line it also depends on other (luminosity sensitive) spectral features which deserve further inspection elsewhere. In conclusion, from the location of the program stars in the $(\beta, [m_1])$ diagram, Orion's new WTTS discussed here are late type stars with luminosity class V or higher. Finally, we want to point out that from their position in the $(\beta, [m_1])$ diagram, 0500.4-1054, 0506.2+0439, 0512.3-0255, 0526.7+0143 and 0535.0-0411 have Hβ clearly in emission (see Fig. 6). Moreover, 0534.7-0423 and 0535.3-0059 have a too large β index. The β indices of the latter should be checked independently, since it suggests a significant mass accretion or loss rate for these objects.

4.2. The $[m_1], [c_1]$ diagram and the new WTTS

For all type of stars, but in particular, in the case of late spectral types (G or later), the [m$_1$] and [c$_1$] diagram is a distance independent observational $(log\ L_*/L_\odot, log\ T_{eff})$ diagram. The reasons for this are that the color indexes m$_1$ and c$_1$ (and hence their reddening free counterparts [m$_1$] and [c$_1$] (see Strömgren 1966, TCDG94 for their definition), are sensitive to T_{eff}, M_V respectively and, to a less degree, to $[Fe/H]$. For late type stars (F5 or later), the loci of luminosity classes V and III define neat sequences in the $[m_1], [c_1]$ diagram (cf. Olsen 1984, Neri et al. 1993, TCDG94, this work). The [m$_1$] and [c$_1$] plot resulted to be an important diagnostic diagram used by us to analyze the *uvby* photometry, since it delivers accurate physical informations of the stars by using only reddening free colors. This allow us to have a first determination of spectral types and luminosity classes for our sample of WTTS. In Fig. 7 we show the location of the new WTTS in the $[m_1], [c_1]$ diagram. It is clear that, except for two stars, all WTTS have spectral types G0 or later in agreement with the spectroscopic results presented in A96. The dashed lines in Fig. 7 indicate the direction of change of luminosity in the diagram at each spectral type. We conclude that most of the observed WTTS have luminosities between classes IV and V, as expected from the theory of stellar evolution (only stars near Stahler's 1983 "birth-line" would be on or near the GS).

4.3. Photometric calibrations

From Fig. 7 it is evident that about half of the observed sample of WTTS in Orion are on or very near the main sequence line in the [m$_1$], [c$_1$] diagram. Since these stars do not show any UV or IR excesses in their SEDs, and their photometric colors and spectra look like those of normal MS stars (Alcalá et al. 1996), we can use the empirical calibrations of the *uvby*-β photometry for luminosity class V stars in order to obtain the principal stellar parameters T_{eff}, M_V, $log\ g$ and $[Fe/H]$ for our sample.

The calibrations and data for late type stars (spectral types G0 to M2) given by Olsen (1984) and for F-type stars by Crawford (1975) are important for this work. These calibrations locate the average position of dwarfs in the c$_1$ and m$_1$ versus $(b-y)_\circ$ diagrams (solid lines in Fig. 8). Also empirical calibrations have been programmed in Fortran 77 for the analysis of $uvby$-β photometry at the University College London (Moon

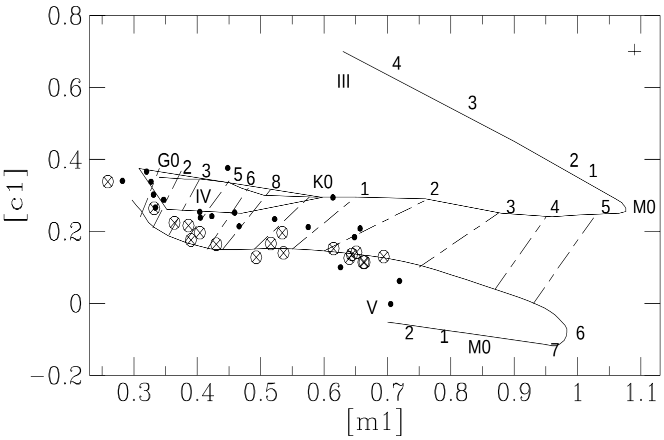

Fig. 7. $[m_1]$, $[c_1]$ diagram of the new WTTS with Strömgren photometry. The locations of the ZAMS, the GS and the luminosity class IV loci are also indicated in the figure. For an explanation of the symbols, see Sect. 5.

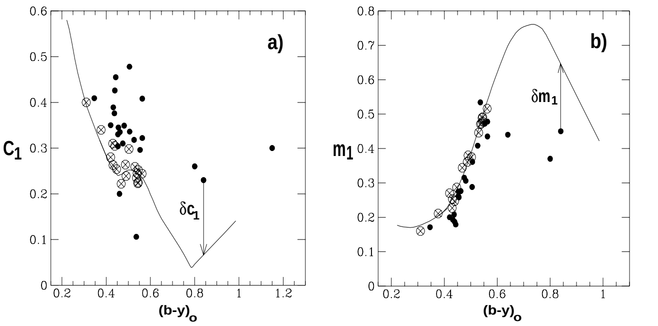

Fig. 8a and b. The intrinsic c_1-$(b-y)_\circ$ and the m_1-$(b-y)_\circ$ diagrams for the program stars. The solid lines represent the calibration for the ZAMS by Crawford (1975) Olsen (1984). The definition of δc_1 and δm_1 are shown (see text). The stars with $\|\delta m_1\| \le$0.05 and $\|\delta c_1\| \le$0.05 are represented with crossed open circles.

1985 and references therein). The programs repeat accurately enough the empirical calibrations by Crawford (1975) and Olsen (1984) for F1-G1 and G2-M2 stars (i.e. $0.22<(b-y)_\circ<0.39$ and $0.39\le(b-y)_\circ<1.00$) respectively. We used Moon's code with minor modifications to fit better Olsen's (1984) calibrations and incorporated to it subroutines to calculate $log\,g$, $[Fe/H]$, stellar radii and distances (Terranegra & Chavarría-K, in preparation).

Olsen (1984) fits $(M_V)_{zams}$ as a function of $(b-y)_\circ$, he gives a calibration of M_V as a linear function of $(b-y)_\circ$, $(M_V)_{zams}$, δc_1 and δm_1. The latter two are defined as δc_1=c_1(star)-c_1(ZAMS) and δm_1=m_1(ZAMS)-m_1(star) (cf. Fig. 8). Note that c_1(star) and m_1(star) are the reddening free indexes. The δc_1 and δm_1 are sensitive to luminosity and metallicity respectively. Thus, the Olsen's M_V calibrations concern magnitude differences within the main sequence band and does not attempt to bridge the gap between luminosity classes IV and III. His reference stars variate in the ranges -0.146$\le\delta c_1\le$0.160 and -0.03$\le\delta m_1\le$0.177, but most of his stars are within $\|\delta m_1\| \le$0.05 and $\|\delta c_1\| \le$0.05. Particularly, we use strictly the latter narrower δm_1 and δc_1 ranges when selecting a subsample of program stars near the ZAMS in this diagram, in order to secure the validity of Olsen's calibrations (see Sect. 5.2).

In a similar procedure as that used for the calibration of M_V with the photometric indices, Olsen (1984) finds linear relations of T_{eff}, $[Fe/H]$ and $log\ g$ with $(b-y)_\circ$, δc_1 and δm_1.

4.4. Physical parameters of the program stars

In Fig. 8 we show the c_1 and m_1 versus $(b-y)_\circ$ diagrams for the Orion WTTS. The intrinsic colors for the program stars were obtain using the dereddening procedures outlined by Crawford (1975) and by Olsen(1984) (see Moon 1985). Note that, while the $(b-y)_\circ$-c_1 diagram is very sensitive to luminosity class, the $(b-y)_\circ$-m_1 diagram is not significantly dependent on $log\ g$ for stars close the MS (Olsen 1984). For stars in the spectral range F1–G1 the M_V's where estimated from the observed β index using Crawford's (1975) (M_V,β) calibration.

The photometric spectral types resulting for our program stars by applying Olsen's Eq. 8 (for G0-K1 dwarf) and Eq. 9 (for K2-M2 dwarf) compare well with those derived spectroscopically in A96 within 2 subclasses, on the average.

We use the Eqs 14 and 16 by Olsen (1984) for population I stars to calculate the $[Fe/H]$ values. We find values in the range $-0.11 \le[Fe/H]\le 0.250$ for our objects. Note that our program stars are extreme population I objects, and, even in the case they happen to be foreground stars, the negative $[Fe/H]$ index reflects a luminosity effect because the program stars are more luminous than their MS counterparts.

Unfortunately, because of the low accuracy of the Olsen's $log\ g$ calibrations (e.g. Olsen's Eqs 19 and 20), our $log\ g$ determinations from the $uvby$-β photometry should be considered tentative. In any case, the values we find for our sample are in the range 4.3 $\le$ log g $\le$ 4.7, about one dex higher than the expected value, if they are located at Orion's SFR.

From the $uvby$-β photometry we obtain also the absolute stellar magnitude M_V and hence the distances of the individual stars. Following the procedure originally outlined by Wesselink (1969), we also applied the surface brightness method with the $(b-y)_\circ$ color as independent parameter to estimate the stellar radii of the program stars. The distance to the stars is obtained from the derredened magnitude $V_\circ$ and M_V delivered by the $uvby$-β photometry. For the colder stars (spectral types F5 or later), we have used a surface brightness F_V vs. $(b-y)_\circ$ calibration from Terranegra & Chavarría-K (in preparation). The stellar radii are found to be in the range $0.78 \le R/R_\odot \le 1.26$.

4.5. Stellar activity and the Strömgren indices

Recent studies by Morale et al. (1996) have shown that the stellar activity may affect the m_1 index in late type stars. Thus, it is important to check how the stellar activity affects the Strömgren indices of the stars in our sample. For this purpose, we used first

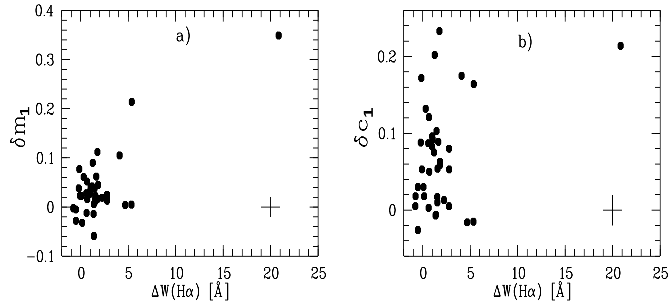

Fig. 9. Plots of $\Delta W(H\alpha)$ versus δm_1 and δc_1.

the ratio of X-ray to bolometric flux, f_X/f_{bol}. X-ray fluxes were estimated in the same way as described in Alcalá et al. (1997). We find a trend for δm_1 to increase as f_X/f_{bol} increases, in agreement with Morale et al. (1996). This trend is not clear, however, for δc_1, also in agreement with Morale et al. (1996) findings.

In order to further confirm these results for our sample, we have also used the Hα line as chromospheric activity indicator. We have computed the quantity ΔW(Hα) = W(Hα)$_{standard}$$-$W($H\alpha$) which is the excess emission of Hα with respect to that of a standard star of the same spectral type. The W(Hα) values for our sample are those reported by A96. The W(Hα)$_{standard}$ values were estimated from the grid of standard stars used by A96 for the spectral type classification.

In Fig. 9 we show the plots of $\Delta W(H\alpha)$ versus δm_1 and δc_1. It is evident the increase of δm_1 as $\Delta W(H\alpha)$ increases (Fig. 9a). Interestingly, the point at about $\Delta W(H\alpha) \approx$21 Å and $\delta m_1 \approx$0.35 in Fig. 9a corresponds to the star RXJ 0513.1+0851, which showed a flare during the spectroscopic observations (see Fig. 3 by A96). This is a further confirmation that the δm_1 quantity is affected by the stellar activity. No trend is seen, however, for δc_1 to increase as ΔW(Hα) increases (Fig. 9b).

In conclusion, we confirm the results by Morale et al. (1996) that the m_1 index is affected by stellar activity, while the c_1 index is not. Thus, the c_1 index can be used confidently to determine luminosity class. However, since the majority of the stars in our sample have δm_1 less than 0.06, the effect on the stellar parameters due to stellar activity is negligible in our sample.

5. Discussion

The association with Orion SFR of the new WTTS is basically sustained by the facts that the LiI λ6708 Å doublet is enhanced in absorption and that a substantial fraction of the program stars have Hα in emission or filled-in in emission. The presence of these features indicate that the primordial lithium has not been destroyed and that they have higher than normal chromospheric activity, indicating the youth of the objects. We now discuss on the possibility that the sample of RASS stars in Orion may be an admixture of both, true Orion WTTS and foreground young stars.

5.1. A subsample of foreground young stars

As already mentioned before, the color indices c_1 and m_1 are luminosity sensitive. An inspection of the locations of our program stars in the [m_1], [c_1] diagram shows that a good proportion of them lie between luminosity classes IV and V (see Fig. 7), well within the valid ranges of Olsen's (1984) calibrations. We have selected the stars in our sample with $uvby$-β photometry that fulfills both narrower valid ranges (in δm_1 and δc_1) of Olsen's (1984) calibrations. The resulting subsample of 18 stars is depicted in Figs. 6, 7 and 8 as crossed open circles. This sample represents about 40% of the 42 stars with $uvby$-β photometry. Furthermore, except for 0500.4-1054, which has Hβ in emission, all the 18 selected stars in terms of their m_1 and c_1 indices also follow the MS within $\|\delta\beta\| <$ 0.05 in the $(\beta, [m_1])$ diagram (cf. Fig. 6). Moreover, most of them have A$_V$ $\leq$ 0.5, V $\leq$ 11.5 and are widely spread westwards from the Orion molecular clouds (cf. Fig. 10). Now, if the stars of this subsample would belong to the Orion SFR, then they would have (low) gravities, comparable with that of giants ($log\ g \approx$ 3.2) and ages of a few hundred thousand years, in opposition to the observations (the stars are significantly more gravitative than giants and have no UV or IR masking effects that would indicate youth).

Based on Crawford's (1975), Olsen's (1984) and Terranegra and Chavarría's (1997, in preparation) calibrations and the numerical code described in Sect. 4.3, we derive the principal parameters of the WTTS of the narrower subsample. The results are summarized in Table 1. From a quick glance of the results in Table 1 it is clear that the WTTS of the narrower sample have M_V, $log\ g$, $[Fe/H]$ and radii R$_*$ values comparable with those of young dwarf stars. The subsample is slightly rich in metals, more luminous, less gravitative and with stellar radii larger than those expected for their ZAMS counterparts of the same spectral type. The subsample stars are located at a mean distance of 130 pc. This distance estimate is based on a method that is well founded observationally and hence difficult to minimize: we have applied the method to determine the distances of (star members of) the Hyades, Coma Berenice and Praesepe clusters with satisfying results (excluding blunders and photometrically apparent nonmembers, typical individual errors $\leq$ 10%). Unfortunately, the same method cannot be applied to the Orion sample studied by TCDG94 because all these objects are strongly variable with very strong activity and near IR and UV excesses. However, for four Taurus stars in the TCDG94 sample (NTT034903+2431; NTT042417+1744; NTT042916+1751 and NTT045226+3013) for which the method can be applied we obtain consistent results for the distance of Taurus within 20%. Note that all these WTTS were also discovered on the basis of X-ray data with the *Einstein* satellite (Walter et al. 1988).

Of the 18 stars of the $uvby$-β subsample, only 0532.5-0421 and 0532.6-0522 (HR Ori) have proper motions with a membership probability of association with Orion's SFR of 90 % or more (McNamara and Huels 1983) and show strong Li I 6708 Å in their spectra. The variable character of HR Ori (Alcalá 1994) may introduce high uncertainties in the measured photo-

Table 1. Stellar parameters for the 18 selected WTTS

Name	M_v	$\log L/L_\odot$	$\log Teff$	$\log g$	[Fe/H]	R1/$R_\odot$	M/$M_\odot$	age (x 10^7yr)	Dist (pc)
0500.4–1054	6.40	-0.30	3.68	4.5	0.00	0.78	1.0	2.0	164
0507.5+1010	5.19	0.02	3.75	4.5	-0.02	0.89	1.0	2.5	104
0509.0–0315	4.96	0.10	3.75	4.3	-0.11	0.98	1.1	2.0	165
0510.3–0330	5.12	-0.02	3.74	4.3	-0.06	0.94	1.0	2.5	152
0511.7–0348	5.68	-0.12	3.73	4.7	0.12	0.80	1.0	2.5	163
0513.4–1244†	4.20	0.32	3.78	—	0.25	1.19	1.2	1.8	205
0515.6–0930	4.83	0.06	3.75	4.6	0.24	1.01	1.0	2.5	105
0517.9–0708	5.86	-0.29	3.72	4.5	0.01	0.79	0.9	3.5	87
0518.0–1146	5.89	-0.30	3.72	4.6	0.05	0.79	0.9	4.0	118
0520.0+0612	6.60	-0.48	3.68	4.6	-0.04	0.78	0.8	3.5	75
0520.5+0616	6.45	-0.42	3.68	4.5	-0.03	0.77	0.9	3.2	106
0520.9–0452†	3.72	0.38	3.81	—	-0.03	1.26	1.3	3.2	144
0529.2–0615	5.40	-0.08	3.74	4.6	0.05	0.85	1.0	2.8	122
0529.4+0041	6.32	-0.43	3.69	4.5	-0.01	0.78	0.8	3.2	142
0530.7–0434	6.35	-0.48	3.69	4.5	0.04	0.78	0.8	4.0	77
0532.4–0713	6.11	-0.30	3.71	4.3	-0.10	0.76	0.9	3.2	158
0532.5–0421	6.39	-0.34	3.68	4.5	0.05	0.79	0.9	3.2	106
0532.6–0522	6.41	-0.41	3.68	4.5	0.04	0.79	0.9	2.8	99

† spectral type outside the validity range for the log$g$ calibration

metric indexes. Also, HR Ori lies very close to the Orion nebula. Moreover, on the basis of high resolution spectroscopy, there are indications that HR Ori may be a spectroscopic binary or multiple star (Covino 1996). Thus, the results of the stellar parameters of HR Ori given in Table 1 are very likely unrealistic. The star most probably belongs to the Orion SFR.

Very interesting indeed is the fact that all 18 stars of the subsample are confined to the Local Bubble and are not at Orion's distance of 460 pc. Basically, if the stars are nearer to the observer than originally thought, then they are more proximal to the MS in a HR-diagram and hence older and less massive than originally assumed. If the absolute visual magnitudes M_V derived from the $uvby$ photometry are correct and applying a bolometric correction (luminosity class V) according to their spectral types, we can fix their location on the $(log\ L/L_\odot, log\ T_{eff})$ diagram. By comparison with the evolutionary tracks by DM94 these stars have masses in the range $0.8 < M_{star}/M_\odot < 1.3$ and a mean age of 2.9 10^7 yr.

5.2. Extinction and spatial distribution

From the frequency distribution of IS extinction we find about 50% of the stars with $0.0 \leq A_V \leq 0.5$ and 50% with $0\overset{m}{.}5 \leq A_V < 1\overset{m}{.}60$. 40% of the low–extinction stars have $A_V \leq 0.2$. The median of the A_V distribution is 0.5. In Fig. 10 we show the spatial distribution of the program stars in two bins of extinction. The shaded symbols represent stars with $A_V \geq 0.5$ and the open circles represent those with $A_V < 0.5$. The stars with the highest extinction tend to be more concentrated towards the denser parts of the molecular clouds while the stars with lower extinction are more or less uniformly distributed on the entire region. This result is enhanced if we restrict the extinction limit to $A_V \approx 0.2$.

We also find that there is a trend for the brightest stars to be the less reddened. To confirm this hypothesis, we have carried out a two sample test. We define the two samples by the magnitude limit V=11.5 which is the peak of the magnitude distribution (see Fig. 2a). In Fig. 11 we show the reddening distribution function of the two samples. The probabilities for the null hypothesis that the reddening distributions are identical according to the Gehan's generalized Wilcoxon test for both permutation and hypergeometric variance and the logrank test are $P(GW)_{per}$ = 0.0002, $P(GW)_{hyp}$ = 0.0001 and $P_{logrank}$ = 0.0006 respectively. Thus, we can reject the hypothesis that the reddening distributions are similar to a high confidence level, and conclude that the brightest stars are less reddened.

Note that the likely foreground stars near the ZAMS of the previous section are, on the average, less reddened (median A_V = 0.21 mag.) and brighter. Then, our above results regarding extinction and spatial distribution, give further support to the hypothesis that some of the low extinction stars with V < 11.5 might be foreground objects and that our sample of new WTTS in Orion might be a combination of foreground young stars and PMS stars associated with the SFR.

5.3. Lithium and spatial distribution

The youth of our program stars is supported by the Li I λ 6708 Å absorption line. A comparison of the Li I results between our and Strom et al. (1990) sample which was observed with comparable resolution shows that both samples occupy the same loci in the $log\ W(LiI), log\ T_{eff}$ diagram and that Li I is overabundant relative to population I stars ($log\ N(Li)$ = 3.8 $\pm$ 0.1 with $log\,N(H)$ = 12; solid line in Fig. 12). However, Li I abundances could be overestimated when derived from middle resolution

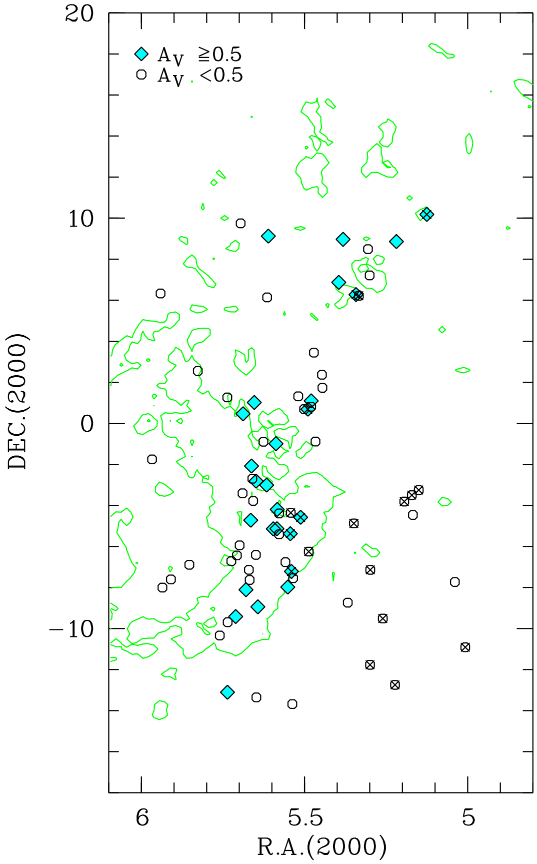

Fig. 10. Spatial distribution of the program stars with $A_V \geq 0.5$ (shaded symbols) and with $A_V < 0.5$ (open circles). The 18 stars satisfying the criteria described in Sect. 5.1 are represented with crossed symbols. The outlines of the CO line radio-survey by Maddalena et al. (1986) are overplotted as a shaded line.

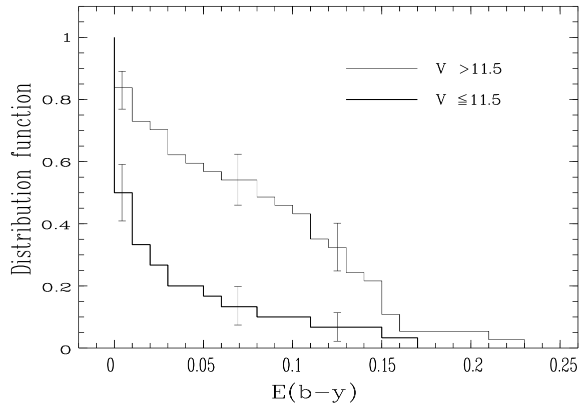

Fig. 11. Reddening distribution function of the bright ($V \leq 11.5$: thick line) and faint ($V > 11.5$: thin line) WTTS samples.

spectroscopic observations, as compared with those obtained from spectra taken at higher resolution (Briceño et al. 1997, Covino et al. 1997).

Soderblom et al. (1993) have analysed the evolution of lithium abundances of solar-type Pleiades, α Persei and Hyades stars. These stars are about one order of magnitude older than typical WTTS but they show enhanced lithium absorption in their spectra with a large scatter which is attributed to the spread of stellar masses and rotation. On the other hand, Briceño et al. (1997) proposed a model in which star formation is assumed to be spatially uniform and steady in time. On the basis of this model, they claim that most of the Li-rich G and K type stars discovered with the RASS in SFRs are not PMS stars, but active 10^8 yr old stars which have dispersed far from their birth sites in molecular clouds, producing a relatively homogeneous distribution of X-ray sources near the galactic plane. These findings immediately raise the question whether the RASS stars in Orion classified as WTTS are 10^8 yr old stars. These are used as arguments by Briceño et al. (1997) to conclude that most of these objects are active ZAMS stars. On the other hand, Palla & Galli (1997) argue that star formation does not take place instantaneously, nor at a constant rate and conclude that the probability to find a large population of old stars among the RASS sources in SFRs is intrinsically very small.

From the arguments given in our discussion, we indeed expect the PMS RASS sample in Orion to be contaminated by other type of active Li-rich foreground young stars. Thus, the important question here is to estimate the degree of contamination. Because of the lack of high-resolution spectroscopy of most of the RASS WTTS candidates, it is difficult to estimate, on the basis of the low-resolution spectroscopy alone, the percentage of relatively older stars which contaminate the RASS samples in SFRs. In the high-resolution spectroscopic study by Covino et al. (1997), it is found that the sample of RASS Li-rich stars in the Chamaeleon SFR is contaminated by a heterogeneous sample of likely field stars, most of them being Pleiades-like, and that this sample represents less than 40% of the original one. Other studies in the Lupus (Wichmann et al., in preparation) and south of the Tau-Aur (Neuhäuser et al. 1997) SFR's, claim a contamination of less than 30%.

A more careful inspection of the Li-data shows that most stars ($\approx$ 60 %) could actually be associated to the Orion SFR. Although we are aware that the lithium equivalent widths for most of the stars reported in A96 are uncertain and that the comparison of data obtained with very different spectral resolutions may be somewhat subjective, we have compared our sample with that by Soderblom et al. (1993) in a lithium (λ6708 Å) equivalent width versus $logT_{eff}$ plot (cf. Fig. 12). This comparison can already give some indications about the percentage of stars falling in the Pleiades area in the W(LiI)–$logT_{eff}$ plane, provided that a correction for the overestimation in the W(Li) values of our sample is applied. A mean correction can be estimated by comparison of the low and high resolution W(Li) values for the same set of stars. Covino et al. (1997) show the relation W(Li)$_{low-resolution}$ vs W(Li)$_{high-resolution}$ for a major sample of Li-rich stars found in Chamaeleon on the basis of the RASS. Their W(Li) residuals are in the range between 0 and 0.15 Å, with some 75% being less than 0.1 Å. Since the mean resolution used for the identification of WTTS candidates

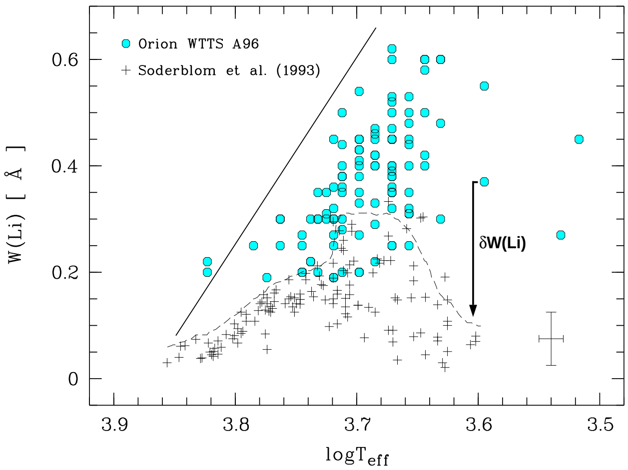

Fig. 12. Lithium (λ6708 Å) equivalent width versus $logT_{eff}$ relation for the program stars (shaded circles). The data of the Pleiades sample by Soderblom et al. (1993) are also overplotted (+). The dashed line represents the upper envelope for the Pleiades. The primordial Lithium abundance, in the $log(H)$=12 scale, is represented by the continuous line.

in the Chamaeleon SFRs is comparable with that used by A96, we use this value to correct the W(Li) values in our sample.

We have derived for each star in our sample the "excess" δW(Li) of the lithium equivalent width relative to the upper envelope for the Pleiades at each T_{eff} (cf. Fig. 12). For the stars below the upper envelope, δW(Li) is obviously negative. At a given temperature interval, δW(Li) is a measure of how much lithium a star has relative to the maximum value for the Pleiades. In order to take into account the overestimation introduced by the low–resolution observations, the limit in δW(Li) was chosen to be 0.1 Å. In Fig. 13 we show the spatial distribution of the program stars in three bins of δW(Li). As expected, the richest lithium stars tend to be in the Orion molecular clouds. This result is in good correspondence with the result of the more extinguished stars (cf. Fig. 11), in the sense that where we see more IS material we see the more Li-rich stars.

Using the δW(Li) = 0.1 limit we also find that more than 50% of our sample stars would have an excess of Li I with respect to the upper-envelope for the Pleiades by Soderblom et al. (1993). Furthermore, on the basis of high-resolution spectroscopic observations of a sub-sample of the Orion stars we find a limit for δW(Li) of less than 0.08 Å(Alcalá et al., in preparation). We then suspect that some 40% of the original Orion RASS stars may be foreground young stars with an age of a few 10^7 yr. The fact that about 40% of the stars with $uvby$-β photometry lie near the luminosity class V line (cf. Fig. 7) supports this. Furthermore, only six of the 18 stars selected with the criteria explained in Sect. 5.1 can be classified as true PMS stars on the basis of their late spectral type (latter than about K0) and a $\delta W(Li) > 0.1$ Å.

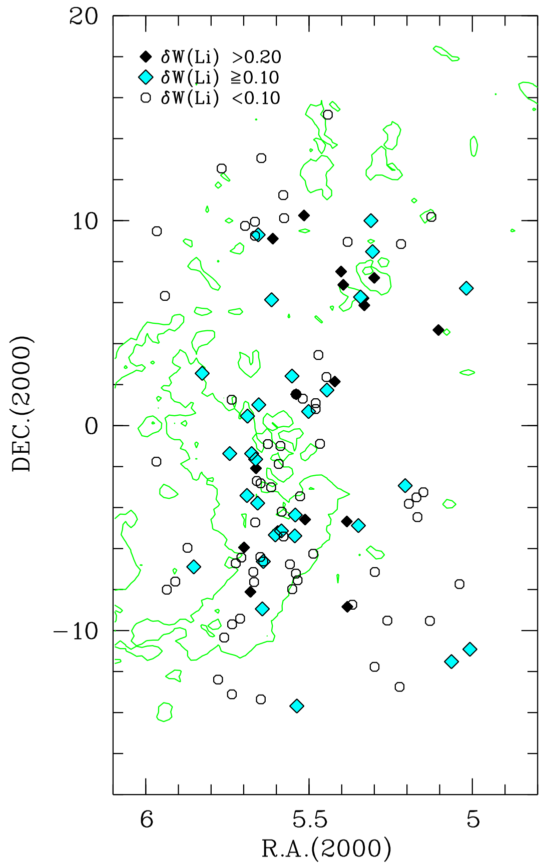

Fig. 13. Spatial distribution of the program stars with δW(Li) > 0.2 (black symbols), $0.1 \leq \delta$W(Li) ≤ 0.2 (shaded symbols) and with δW(Li) < 0.1 (open circles). The outlines of the CO line radio-survey by Maddalena et al. (1986) are overplotted as a shaded line.

5.4. On the origin of the widely spread PMS stars

Recent investigations have addressed the problem of the origin of the young WTTS located very far from molecular clouds (Sterzik et al. 1995; Sterzik & Durisen 1996; Feigelson 1996). One possibility is that some of the young widely-spread WTTS may have been ejected from the clouds by three body interactions (Sterzik & Durisen 1996). These run-away T Tauri stars (RATTs) loose their circumstellar disk in the close encounters. A velocity dispersion of 3 km/s would be sufficient to explain the presence of 10^7 yr old stars located several parsecs away from SFR's. Another possibility is that the widely spread WTTS have been formed *in-situ* from molecular gas which has already been dispersed (Feigelson 1996). Now, the location and age of the young PMS stars reported here and the absence of a parent cloud is in agreement with the possibility that star formation was induced when the Local Bubble was formed. It has been suggested that the Local Bubble was formed by supernovae outbursts or by a high velocity cloud hitting the galactic disk a few 10^7 yr ago. In such a scenario, we should expect to observe young, active and rich in Li I stars in all directions where the bubble exists. Observations seem to show that such stars indeed exist (Favata et al. 1993, 1995; Tagliaferri et al. 1994; Jeffries et al. 1994, 1996).

Another possibility is that many of the RASS foreground stars in the direction of Orion are Gould's Belt members. The ages reported in table 1 are consistent with Gould's Belt age. Moreover, the analysis of the spatial distribution of RASS sources in more than 5000 square degrees in the general direction of Orion, revealed a large-scale structure that crosses the field in a $\approx$ 20 deg broad lane, located $\approx$ 15 deg south of the galactic plane (Sterzik et al. 1997). The structure generally coincides with the Gould Belt in that direction of the sky. Nevertheless, given the errors involved in the determination of the ages by comparison with different PMS evolutionary tracks, we cannot definitely distinguish between Gould's Belt stars and active pleiades-age stars among the foreground sample.

6. Conclusions

We have analysed the spectroscopic and photometric data of 60% of the RASS lithium stars widely spread in the direction of the Orion SFR. All these stars can be classified as true WTTS if they are at the distance of the Orion SFR. However, the analysis of extinction distribution, lithium equivalent widths and spatial distribution give evidences that the sample of RASS lithium stars is an admixture of different populations of stars namely: *bona-fide* WTTS physically associated with the Orion SFR and foreground lithium X-ray emitting stars with ages comparable to that of the Gould Belt. The analysis of the $uvby$-β photometry supports this result allowing us to confirm that at least part of a subsample of the RASS lithium stars are foreground young stars not associated with Orion. We cannot exclude, however, that many of the foreground objects are pleiades-age stars. Undoubtly, an extensive study of the lithium strength in the RASS samples in SFRs based on high-resolution spectroscopy, together with a study of the kinematic behavior (radial velocities and proper motions) as well as the precise determinations of parallaxes of the program stars will shed important light to elucidate this matter, in particular, the high quality Hipparcus parallax determinations of program and field stars that will enable us to discriminate between Orion's WTTS and foreground stars and to disclose their true origin.

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