Revista Mexicana de Astronomía y Astrofísica, **29**, 137-140 (1994)

DIAGNOSING PRE-MAIN SEQUENCE STARS PHOTOMETRICALLY

Carlos Chavarría–K.
Instituto de Astronomía, Universidad Nacional Autónoma de México
and
Max–Planck Institut für Astronomie, Heidelberg, Germany

RESUMEN

Se da una revisión parcial de la fotometría en el óptico y cercano infrarrojo aplicada al estudio de estrellas asociadas a regiones de formación estelar, y se discuten resultados recientes.

ABSTRACT

A partial overview of optical and near IR photometry applied to the study of stars associated with star forming regions is given and some recent results are discussed.

Key words: **TECHNIQUES: PHOTOMETRIC — HERTZPRUNG–RUSSELL DIAGRAM — STARS: PRE-MAIN SEQUENCE**

1. INTRODUCTION

Signatures in the stellar spectrum and photometric properties, together with the simultaneous fulfillment of morphologic and kinematic constraints, are the necessary tools to determine the pre-main sequence (PMS) nature of a star. Usually, the objects are selected in such a manner that they fulfill the morphological conditions; i) they have a reflection nebulosity, and ii) they are associated with dark clouds or obscured sky regions. There are exceptions (e.g., Herbig 1994). Unfortunately, many star forming regions (SFRs) have not been studied kinematically, but should such a study be available, it would give independent information about the membership of stars to a particular sky region. The spectroscopic features are a line- and continuum-emission spectrum superposed to a photospheric spectrum of a B or later type star. The emission spectrum is constituted by hydrogen (Lyman, Balmer, Paschen, Bracket line series and continuum), low excitation permitted and forbidden lines of neutral and once ionized metals, or any combination of these constituents (e.g., Herbig 1960, 1962; Finkenzeller & Mundt 1984). These stars are called classic T Tauri (CTTS) and Herbig Ae and Be stars. Detailed spectroscopic studies with model atmospheres of Ae and Be stars show that they have lower surface gravities than their dwarf counterparts (an indication of their PMS nature, e.g., Strom et al. 1972). But it is the photometry which enables us to unambiguously determine their evolutionary status when the stars are fixed in the $(L/L_{\odot}, T_{eff})$– or H-R diagram, with the advantage that this is obtained with relative ease. Optical photometry of PMS stars shows that these objects are typically located $0.^{m}5$ or more above the main-sequence (MS) in a color-magnitude (CM) diagram, indicating that the stars are larger and therefore of lower surface gravity than their dwarf counterparts. An exception are the so-called *subluminous* stars (see below). In most cases, IR photometry has revealed the presence of a circumstellar (CS) envelope which veils the central star (e.g., Mendoza 1966, 1968). It is the IR photometry, combined with the optical and, when available, with the UV photometry that makes possible the determination of the bolometric luminosity $(L/L_{\odot})$ of these veiled objects. The PMS–stars lie above and to the right of the MS in the H-R diagram. This is interpreted, in terms of the theory of stellar evolution, as stars on their convective or radiative quasi-hydrostatic contraction phase towards the main sequence. Due to the presence of active envelopes or disks, an estimate of the basic stellar parameters is, in some cases, uncertain, and is now a field of intense research (e.g., Kenyon et al. 1993; Bouvier & Bertout 1992; Hartigan et al. 1991, and references therein). Over a decade ago, a new subset of stars in the proximities of SFRs was discovered by spacecraft-bound observations on the basis of their intense (and variable) X-ray fluxes alone (Walter & Kuhi 1981; Feigelson & Kriss 1981; Montmerle et al. 1983). Backup ground-bound optical and IR observations show that these X-ray stars are objects with almost normal late-type stellar photospheres, chromospheric lines (Mg II–D & Ca II–H+K) and the Hα line in emission (W(Hα) $\leq$ 5 A), and LiI λ 6707 A enhanced in absorption. Most important, we know from their optical and IR photometry that they are barely, if at all veiled, that they occupy the same locus in the H-R diagram as other well known PMS-stars (i.e., CTTS), and hence share the same nature. However, they are more extensively distributed throughout the dark clouds than CTTS (e.g., Alcalá 1994; Krautter et al. 1994). They are now called weak-line T Tauri stars (WTTS). Finally, CCD optical and near IR imagery of selected SFRs has recently reveiled low mass stars which are spatially concentrated and well-embedded in their parent clouds. These objects are in an early phase of star formation (Moreno-Corral et al. 1993; Zinnecker et al. 1993; Strom 1994, Eiroa & Casali 1992, and references therein). Their PMS nature is photometrically established when the embedded stars are fixed in CM and two-color diagrams.

2. RECENT PHOTOMETRIC RESULTS

2.1. Subluminous PMS-Stars

Some stars associated with SFRs (e.g., Taurus-Auriga, CO Orionis, Corona Austrinae, ρ Ophiuchi, NGC 2264) which have a high kinematic probability of membership and an emission spectrum superposed on an intermediate- or late-type stellar photosphere are located below the main sequence in a CM-diagram (e.g., Walker 1956). The star W90 (= LKHα 25) is perhaps the most studied of these objects (cf. Rydgren & Vrba 1987). Poveda (1965) suggested that these subluminous stars suffer gray extinction caused by large CS dust particles which indiscriminately absorb light in the optical, re-emitting it in the infrared. Contrary to this, Ambartsumian has suggested that the subluminous stars are PMS objects in an earlier formation stage than the CTTS or the even older flare stars and are denser bodies than their MS counterparts. As these objects evolve, they expand and become T Tauri stars (cf. Ambartsumian & Mirzoyan 1982 and references therein). This is not sustained by the present physics, and it leads to contradictions with the observations. Another explanation is that these objects might suffer from "blue" veiling. This would cause the stars to shift towards bluer colors with little or no change in the visual brightness in the CM-diagram (Warner et al. 1977 and references therein). It is the quasi-simultaneous optical and IR photometry and the MK spectral types derived spectroscopically from such objects that enable us to fix their location in the H-R diagram and show that they are undoubtly PMS-stars in their gravitational contraction phase towards the MS. The stars remain more luminous than their MS counterparts, even if we take into account an autoluminous CS disk (cf. Neri et al. 1993; Mújica et al. 1994, and references therein). Furthermore, the stars studied so far present UV and IR flux excesses, supporting the presence of an active disk in such objects (see next section). In one case, Mújica et al. (1994) found the LiI λ 6707 A enhanced in absorption, but spectroscopic observations with higher dispersion ($\geq$ 3 A/px) and better signal-to-noise are encouraged in order to form a conclusion on this property of the *subluminous* stars. The spectral types of the *subluminous* stars observed by Mújica et al. range from early A to early M.

2.2. On the Driving Mechanisms of the Variability in PMS-Stars

Most PMS-stars are variable. Small amplitude ($\Delta m_v < 0.^m7$) and short periodic ($\approx$ days) variations in the optical (multifilter) light curve can be fitted with a simple (dark or bright) spot model consisting of a black body approximation of the rotating star and spot, where the spot "size and temperature" are determined in terms of their stellar counterparts (cf. Vrba et al. 1993; Bouvier et al. 1993; Covino et al. 1992, and references therein). The BY-Draconis type variability and X-ray emission observed in these objects are related to (enhanced) solar-magnetic activity, i.e., manifestations driven by magneto-dynamo processes. If the variations have a large amplitude ($\geq 0.^m7$) and are apparently erratic, or if these changes occur over a long time scale (FU Orionis- or DR Tau-type stars), they are most probably caused by a viscous and differentially rotating CS disk accreting with variable rate, mass onto the slower rotating star, or by clumps of CS matter in Keplerian orbits around the central object. In the former case, correlated IR and UV flux excesses should be observed, while, in the latter case, the amplitudes of the variations follow an interstellar extinction law (e.g., Mújica et al. 1994, Covino et al. 1992). The "blueing" effect observed in certain PMS-stars (i.e., a star turns bluer in the $U-V$ and $B-V$ colors as V diminishes but the spectral type remains constant) is explained in terms of extinction/scattering of light due to a fluffy CS disk (Gahm et al. 1993).

2.3. CCD Imagery of Localized Star Formation in Dark Clouds

Recently, spatially resolved intermediate IR and radio observations in the CO and other molecular lines ave shown that the dust and molecules efficiently cool the outer-layers of dust or molecular clouds, particularly ı the vicinity of the ionization fronts at the bright Hα knots and rims of a dark-cloud/H II interface region.)n the other hand, the forces due to the ionization front and the backflowing ionized gas act on the surface of ıe neutral/ionized boundary, together with the pressure of the UV–radiation field and the surrounding H II ɜgion, compress the dark cloud locally with little variation of the temperature and hence reduce the Jeans' ıass to solar or subsolar sizes in the vicinity of the interface. The density and the temperature of CO vary y factors of $\approx$ 30 and $\leq$ 2, respectively, within a linear dimension of 0.1 pc or less, when traversing the front :om the ionized to the neutral region (e.g., Nakano et al. 1989). The small temperature gradient of the dust t such a location is confirmed by spatially resolved intermediate IR observations. Finally, if stars are to be ɔrmed in such locations, the time scale τ must be of the order of the characteristic linear dimension of the ɔnization front ($\approx$ 0.1 pc) divided by its intruding velocity (v $\approx$ 2 km s^{-1}), that is $\tau \approx 10^5$ yrs. CCD optical nd near IR imagery has revealed the formation of low mass stars in such an environment (e.g., Moreno-Corral t al. 1993; de Lara et al. 1994; Zinnecker et al. 1993, and references therein). An inspection in the CM- and wo-color diagrams of stars associated with bright knots and rims [e.g., $(I, V-I)$ or $(K, J-K)$ and (α_R, I) r $(J-H, H-K)$, respectively] discloses their PMS nature and reveals their associated CS envelopes or disks ɜ.g., Moreno-Corral et al. 1993; de Lara et al. 1994, Chavarria-K. et al. 1989). Hα emitting stars stand out :om the normal stars in the (α_R, I) diagram, giving an important clue to the presence of a CS envelope and ılfill an important condition to belong to the young Orion population stars.

2.4. Optical and Near IR Photometry of *ROSAT* Weak-line T Tauri Stars in Orion

The *ROSAT* all-sky survey of Orion detected 820 sources. About one third were found to coincide spatially rith optical counterparts contained in existing catalogues (Alcalá 1994; Alcalá et al. 1994). Backup groundounded intermediate dispersion spectroscopy of 131 X-ray sources reveals 81 new WTTS. Their $UVB(RI)_C$ nd $JHKL(M)$ photometry shows that i) WTTS lie, as expected, above the MS in a CM-diagram, ii) none f them showed significant UV- or IR-flux excesses (thus the normal bolometric corrections are applicable to btain luminosities), and they occupy the same region in the H-R diagram as the CTTS, iii) and iv) from omparison of the observations with evolutionary tracks of contracting star models in the H-R diagram, and rithin the errors expected, most of the stars fall on or near an isochrone curve (i.e., coeval star formation)and heir ages are $\approx 1.5 \times 10^6$ yrs, very similar to those observed in other regions, and finally v) there is a selection ffect in the sense that only the intrinsic brighter X-ray sources and hence more massive WTTS in Orion were bserved spectroscopically and photometrically. Results (iii) and (iv) are very interesting: it has been suggested arlier that stars seem to have their "internal clocks" reset by an external cause such as a supernova outburst Walter et al. 1993), but it is not casual to observe about the same age and coevality in other SFRs where such . perturbation is not obvious (e.g., Bouvier & Appenzeller 1992; Alcalá 1994, Strom 1994). Contrary to an arlier belief, we find that the WTTS are, on average, only about a factor of 1.5 older than the CTTS in Orion see also Bouvier & Appenzeller 1992; Strom 1994, Walter et al. 1994). These results will help us to understand he star forming process in general, and the initial luminosity and mass functions of SFRs in particular (cf. ;innecker et al. 1993).

2.5. Strömgren and Hβ Photometry of Stars Associated with Star Forming Regions

uvby-β photometry of stars associated with SFRs combined with model atmospheres or empirical alibrations has proved to be a good tool to study PMS-stars and their environments. From a study of $\approx$!00 stars in 8 SFRs (Terranegra et al. 1994; Chavarría-K. et al. 1994) the following emerges: i) the colornagnitude $(V, b-y)$ diagram of an association or cluster is obtained with relative ease, and the regions studied ıave the expected properties in such a diagram; ii) model atmosphere grids disagree with empirical calibrations or stars later than about G2, iii) reliable MK spectral types are obtained from reddening free colors ($[c_1]$,$[m_1]$ ınd $[u-b]$) and corresponding two-color diagrams; iv) an estimate of the surface gravity can be derived, provided hat the reddening-free indices are redefined with coefficients corresponding to an outer-cloud IS extinction law;) Hβ emission stars stand out in the (β,$[m_1]$) diagram, particularly Herbig Ae and Be stars; vi) from a quick ;lance at the loci of PMS-stars in the (β, m_1) diagram, one is also able to estimate spectral types fairly well; (vii) t provides a powerful tool for the determination of the nature of apparently faint stars associated with fairly ınknown regions using only photometric methods, and (viii) the total to selective extinction ratio (A_v/E$(B-V)$ ır R_v) is steeper than normal, and the coefficients α_m = E(m_1)/E$(b-y)$ and α_c = E(c_1)/E$(b-y)$ are smaller n their absolute value than the usually adopted ones. Finally, it should be interesting to study the stellar radii ısing the bolometric luminosity, and with help of the surface brightness method (e.g., Rojo Arellano & Arellano 'erro 1994).

It is a pleasure to thank my colleagues and collaborators M.A. Moreno-Corral, L. Terranegra, E. de Lara J.M. Alcalá, E. Covino, R. Mújica, and L. Neri. The author has benefited from discussions with A. Poveda and E. Mendoza. Financial support from DGAPA, UNAM is heartily acknowledged.

REFERENCES

Alcalá, J.M. 1994, Dissertation, University of Heidelberg, Germany

Alcalá, J.M., Krautter, J., Terranegra, L., Schmitt, J.H.M.M., Chavarría-K., C. & Covino, E. 1994, RevMexAA 29, 209

Ambartsumian, V.A., & Mirzoyan, L.V. 1982, Ap&SS, 84, 317

Bouvier, J., & Appenzeller, I. 1992, A&AS, 92, 481

Bouvier, J., & Bertout, C. 1992, A&A, 263, 113

Bouvier, J., Cabrit, S., Fernández, M., Martin, E.L. & Matthews, J.M. 1993, A&A, 272, 176

Chavarría-K., C., Moreno-Corral, M.A., Hernández-Toledo, H. Terranegra, L., & de Lara, E. 1994, A&A, 283 963

Chavarría-K., C., Leitherer, C., de Lara, E., Sánchez, O., & Zickgraf, F.-J. 1989, A&A, 215, 51

Covino, E., Terranegra, L., Franchini, M., Chavarría-K., C., & Stalio, R., 1992, A&AS, 94, 273

de Lara, E., Chavarría-K., C., & Moreno-Corral, M.A. 1994, RevMexAA, 29, 209

Eiroa, C., & Casali, M.M. 1992, A&A, 262, 468

Feigelson, E.D., & Kriss, G. A., 1981, ApJ, 248, L35

Finkenzeller, U., & Mundt, R., 1984, A&AS, 55, 109

Gahm, G. F., Liseau, R., Gullbring, E.G., & Hartstein, D. 1993, A&A, 279, 477

Hartigan, P., Kenyon, S., Hartmann, L., Strom, S.E., Edwards, S., Welty, A.D., & Stauffer, J. 1991, ApJ, 382 617

Herbig, G.H. 1960, ApJS, 4, 337

______. 1962, Advances A&A, 1, 47

______. 1994, RevMexAA, 29, 17

Kenyon, S.J., Calvet, N., & Hartmann, L. 1993, ApJ, 414, 676

Krautter, J., Alcalá, J.M., Wichmann, R., Neuhäuser, R., & Schmitt, J.H.M.M. 1994, RevMexAA, 29, 41

Mendoza, E.E. 1966, ApJ, 143, 1010

______. 1968, ApJ, 151, 977

Montmerle, T., Koch-Miramond, L., Falgarone, E., & Grindlay, J. E. 1983, ApJ, 269, 182

Moreno-Corral, M.A., Chavarría-K., C., de Lara, E., & Wagner, S. 1993, A&A, 289, 1

Mújica, R., Chavarría-K., C., Corral, L., & Neri, L. 1994, RevMexAA, 29, 214

Nakano, M., Tomita, Y., Ohtani, H., Ogura, K., & Sofue, Y. 1989, PASJ, 41, 1073

Neri, L.J., Chavarría-K., C., & de Lara, E. 1993, A&AS, 102, 201

Poveda, A. 1965, Bol. Obs. Tonantzintla y Tacubaya, 4, 15

Rojo Arellano, E., & Arellano Ferro, A. 1994, RevMexAA, 29, 148

Rydgren, A.E., & Vrba, F.J. 1987, PASP, 99, 482

Strom, K.M., Strom, S.E., Allen, L., Kepner, J., & Gordon, S. 1994, RevMexAA, 29, 30

Strom, S.E., Strom, K.M., Yost, J., Carrasco, L., & Grasdalen, G. 1972, ApJ, 173, 353

Terranegra, L., Chavarría-K., C., Díaz, S., & Díaz, L.M. 1994, A&AS, in press

Vrba, F.J., Chugainov, P.F., Weaver, W.B., & Stauffer, J.S. 1993, AJ, 106, 1608

Walker, M. 1956, ApJS, 2, 365

Walter, F.M., & Kuhi, L.V. 1981, ApJ, 250, 254

Walter, F.M., Vrba, F.J., Mathieu, R.D., Brown, A., & Myers, P.C. 1994, AJ, 107, 692

Warner, J.W., Strom, S.E., & Strom, K.M. 1977, ApJ, 213, 427

Zinnecker, H., McCaughrean, M., & Wilking, B. 1993, in Protostars and Planets III, ed. E.H. Levy & J.I Lunine (Tucson: University of Arizona Press), p. 429

Carlos Chavarría-K.: Instituto de Astronomía, UNAM, Apdo. Postal 70-264, 04510 México, D.F., México e-mail: chavarri@astroscu.unam.mx.