Revista Mexicana de Astronomía y Astrofísica, **29**, 17-22 (1994)

STAR FORMATION: SOME ISSUES THAT NEED ATTENTION

G. H. Herbig
Institute for Astronomy, University of Hawaii

RESUMEN

El progreso científico ocurre a diferentes velocidades, los descubrimientos más espectaculares son inesperados, o el resultado de ráfagas de inspiración. En seguida viene la creación de nuevas estructuras conceptuales y la exploración de sus consecuencias. Finalmente está la acumulación paciente y sistemática de información nueva. El descubrimiento de Mendoza del exceso infrarrojo en estrellas T Tauri, pertenece claramente a la primera categoría, por ser sorpresivo y por sus ramificaciones subsecuentes. Tales descubrimientos espectaculares no pueden planearse o anticiparse, por lo que este artículo trata de asuntos observacionales de la segunda categoría: temas en el área de formación estelar (como creemos entenderla) que necesitan clarificación, complicaciones que permanecen sin solución, algunas preguntas que necesitan mayor atención. Estos temas son: 1) formación estelar en cúmulos muy densos, 2) estrellas jóvenes alejadas de lugares obvios de formación estelar, 3) el hecho cada vez más obvio que no todas las estrellas nacen de la misma forma, 4) el cómo acomodar estrellas tales como β Pic en el esquema convencional de evolución estelar temprana, 5) la detección óptica de estrellas muy jóvenes y muy masivas y 6) las estrellas *flash* y las estrellas *flare*: ¿hay alguna diferencia entre ellas?

ABSTRACT

Scientific progress takes place at different velocities, the most spectacular being inspired flashes of insight or unexpected new discoveries. Next, is the creation of new conceptual structures and the exploration of their consequences. Lastly is the patient and systematic accumulation of new information. Mendoza's discovery of infrared excesses in T Tauri stars clearly belongs in the first category because of its surprise and because of its subsequent ramifications. Such spectacular discoveries cannot be planned or anticipated, so this paper deals with observational issues of the second kind: matters in the area of star formation (as we believe we understand it) that need straightening out, complications that remain unresolved, some questions that need more attention. These are: (1) star formation in very dense clusters, (2) young stars far from any obvious birthplace, (3) the increasingly obvious fact that not all stars are born equal, (4) how to fit stars like β Pic into the conventional picture of early stellar evolution, (5) the optical detection of very young, very massive stars, and (6) 'flash' and 'flare' stars: is there a distinction?

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

I am quite aware of the statement that 'when one begins to talk about science, it usually means that he ıas stopped doing science'. So I realize what you will think when I begin, not by discussing scientific results but ·ather, by attempting to classify what it is we do: to categorize our activities as observers or observationally-nclined astronomers. But please bear with me.

I see our activities, or our product, as falling in one of three categories:

Level 1: these are the great breakthroughs, discoveries that have a major impact upon their subject or ıpon all science. Often they occur as the result of accident, inspiration, or pure serendipity. Often they almost fall into the discoverer's hands as the result of some new technological opportunity. Few of us in our lifetime are fortunate enough to experience such a dazzling revelation. Examples: Newton and the apple, Jansky's discovery of radio radiation from the Galactic Center, Schmidt's recognition of quasar redshifts. I think that Eugenio Mendoza's discovery of infrared excesses of pre-main sequence stars (Mendoza 1966, 1968) falls in this category, both on the grounds of surprise and because of its subsequent ramifications.

Level 2: the exploration, extension, and testing of conceptual structures. An example: most of us are reasonably comfortable with the present-day picture of star formation from molecular clouds. But clearly many of the complications and consequences of that picture are still to be worked out. The elucidation of such questions occupy the full-time attention of many of us here, and of dozens – perhaps hundreds – of astronomers elsewhere. It is issues at this level to which I want to devote my talk. But first I want to speak in praise of Level 3 activity.

Level 3: the amplification and elaboration of examples: to enlarge the database, to improve the statistics to reassure ourselves that the phenomenon (whatever it is) is a general one. Much astronomical activity is of this kind. It may not be the most creative or exciting science, but it has to be done, if for no other reason than to protect us from our own wishful thinking.

We stand at the apex of a huge pyramid of Level 3 information that has been gathered for us by the astronomers of the past, and it is our obligation to add some solid and significant bricks to that structure. How could we possibly work without the catalogues of coordinates, proper motions, spectral types, photometry,.. that we have inherited? We are hugely indebted to those who have measured for us light curves, v sin i's lithium abundances, column densities,... and so much more.

Let us be grateful to those who have amassed this precious information for us. For example, look through the *General Catalog of Variable Stars (GCVS)*, all 4 volumes of it, and reflect upon the enormous effort represented therein. I have the impression that not until relatively recently was there an overall sense of what variable stars and their activities represented. Before, it was botany: the goal was to name it, to classify it, put it in a labelled box (I like this analogy, but it is Walter Baade's, not mine). It was when the imperatives of hydrogen burning – time scales, origins, alternative energy sources – were recognized that this jungle began to make sense.

Whatever it was that motivated the variable star investigators of the past, one wonders how the subject of pre-main sequence evolution would have developed had not that vast database been assembled: if the variable star catalogues of Prager and Schneller (predecessors of the *GCVS*) had not existed for Alfred Joy to browse through, to cause him to mull over those odd stars like T Tau and RW Aur and S CrA, and to incite him to take their spectra. We all know what happened thereafter: many of our careers are a consequence.

So, having made the point that Level 3 activity often provides important although perhaps not immediate dividends, and that there may be discoveries to be made in the library as well as at the telescope, I want to return to Level 2 matters, to discuss some interesting questions of pre-main sequence evolution that I think need exploration, or straightening out.

1. What fraction of star formation takes place in very dense clusters which subsequently disperse? This issue has arisen recently as the result of the discovery, thanks to infrared arrays, of several heavily- obscured clusters in molecular clouds. It is reminiscent of a similar debate that engaged some of us in the 1950's when theorists believed that stars could form only through the fragmentation of very massive clouds. A paper by Roberts (1957) was often (and still is) cited in support of the view that the great majority, if not all, OB stars form in clusters or associations. Although that claim rested on some primitive information on OB statistics that by now is quite obsolete, I think most of us would agree with the conclusion. But are the clusters and associations that Roberts considered the relaxed remnants of the very dense aggregates like the Orion Trapezium cluster or the cluster in NGC 1579 (Barsony, Schombert, & Kis-Halas 1991)? That is a question that I don't think can yet be answered.

It may not be appreciated that the mass density in the Trapezium Cluster is comparable to that in globular clusters, although its total mass is considerably less. Figure 1 is a log-log plot of central mass density vs. core radius for globulars, the data from Peterson & King (1975). Lines of constant core mass cross the diagram from upper left to lower right; the globular cluster points are enclosed between lines of $M_c = 3 \times 10^3$ and 1×10^5 solar masses. The point representing the Trapezium Cluster is located at the mass density and half-mass radius determined by Samuel (1993). The line extending to the right shows how far the Trapezium point would migrate if the half-mass radius were converted to core radius by King models.

We need to find more systems like this, to investigate how —or if —they evolve into clusters like NGC 2264 and how many members they shed in the process.

2. We have become accustomed to the idea that T Tauri stars (TTS) cannot wander far from their

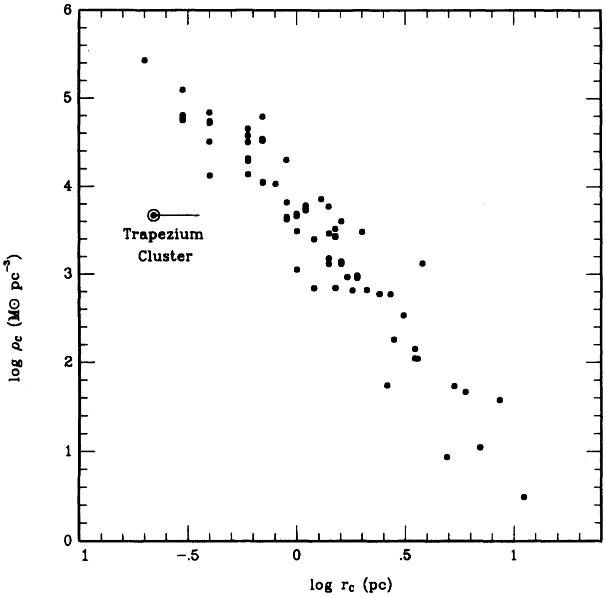

Fig. 1. Central density vs. core radius for globular clusters (data from Peterson & King 1975). The circled point for the Trapezium Cluster represents its location if half-density radius (from Samuel 1993) is used for core radius. If conversion to core radius is made by a King model, the point would lie somewhere along the short horizontal line.

birthplaces before they lose their TTS characteristics. Nevertheless examples are known of what appear to be genuine TTS far from any obvious site of star formation. TW Hya was the first of these (Rucinski & Krautter 1983), but now there are more examples: de la Reza et al. (1989); Gregorio-Hetem et al. (1992). Although one of these stars may be a weak continuum point source, no convincing evidence of extended interstellar material has been found at any of those positions (Rucinski 1992). What does this mean? Can some other phenomenon mimic the TTS spectrum? Or is there some way the TTS phenomenon be prolonged? At the least, we would welcome accurate proper motions for some of these objects to see if they might be high-velocity escapees from some distant molecular cloud. A search has already begun for TTS in the high-latitude molecular clouds discovered by Magnani, Blitz, & Mundy (1985) (the subject is reviewed by Blitz 1991), to see if star formation can take place at those low densities and in those unconventional sites.

3. For many years one has tended to think of TTS as single, lacking the complications that might ensue if some were close binaries. Yet there are close binaries on the main sequence that presumably once passed through the TTS stage. There is now strong evidence that the fraction of optically-resolvable binaries among TTS is comparable to that among main-sequence stars in the same mass range: see the reviews by Ghez, Neugebauer, & Matthews (1992), by Leinert et al. (1992), by M. Simon (1992), by Zinnecker, Brandner, & Reipurth (1992), and by Reipurth & Zinnecker (1993). There seems no reason why this should not be so for closer systems as well: the subject of pre-main sequence spectroscopic binaries is reviewed by Mathieu (1992). Quite aside from the complications that binaries would have on color-magnitude diagrams, one has to ask what would be the spectroscopic consequences of interaction between the two components, and whether any of the bizarre phenomena observed in TTS might be understood in that way.

Certainly not all stars are born equal: aside from the matter of duplicity or multiplicity, studies of the rotation and surface activity of stars in young clusters and on the main sequence indicate very strongly that some single stars must be endowed from birth with more angular momentum than others (Soderblom 1991; T. Simon 1992). It may be that there are other characteristics in which stars differ from one another, as the result of different sites or different circumstances of the formation process, and are discoverable if we are sufficiently perceptive.

My point is that early stellar evolution is certainly more complicated than we might like, that stars are not beads on well-defined wires stretched across the H-R Diagram. We should welcome this, and be alert to things that do not fit, because sometimes that is where Level 1 discoveries lie hidden.

4. We ought to be able to reconcile our ideas about early stellar evolution with the phenomenon of dust shells that have been discovered around several A-type stars in the solar neighborhood. Notable among these are α Lyr, α PsA, and especially β Pic, where an elongated nebulosity extending to 12″ or more from the star has been imaged directly by coronagraphic techniques, most recently by Golimowski, Durrance, & Clampin (1993). The subject has been reviewed comprehensively by Backman & Paresce (1993). Interesting analogies have been drawn between β Pic and the early history of the solar nebula and the planetary system, and what our zodiacal light might have looked like in the early days of the Sun. One need not be concerned that remnants of an original circumstellar disk still survive around an A5 main sequence star (if β Pic can be considered that in view of its peculiar spectrum, under-luminosity, and low [Fe/H]), because Paresce (1991) has estimated its age since leaving the ZAMS as about 10^8 years, and we know from the history of the lunar surface that the cleanup of large masses in the solar nebula continued for about 8×10^8 years.

Nor is there a problem with the present location of β Pic: even if it were freshly-arrived on the ZAMS, its space motion with respect to the Sun (21 km s^{-1} according to Whitmire, Matese, & Whitman 1992) is large enough and the contraction time for 1.5 $M_\odot$ is long enough for the star to have reached the solar neighborhood from any one of several nearby molecular clouds, although 2×10^7 years ago some of the sites of active star formation may not have been the ones we know today.

If all this is so, then one wonders why even brighter versions of such nebulae do not seem to be present around even younger A-type stars, such as in Orion and h, χ Per.

5. Current theory tells us that very massive stars reach the main sequence before their dust shells have dissipated. There has been interesting speculation that such objects are detectable at cm wavelengths as ultra-compact H II regions (Churchwell 1990, 1991) or as compact high-luminosity infrared sources (Henning 1991) in molecular clouds. There must be a time, from the very fact that OB stars are observed on the main sequence, when these 'cocoons' have been sufficiently dissipated that the central stars become optically detectable. The phenomenon of emergence would be an interesting area of investigation. We probably know already a few examples of massive stars in this transition stage: the BN Object in the Orion Nebula, MWC 349 in Cyg OB2, and the central star in S 106, but much work remains to be done. When one looks at the descriptions of some of the curious stars observed in the 1940's and 1950's by Struve and Swings, and by Merrill and his colleagues, and ignores those that are obviously interacting binaries, old novae, or symbiotics, there remain some interesting objects that deserve modern attention.

6. There is another area, at the opposite end of the mass spectrum, that I think also deserves examination with modern equipment. These are the 'flash' variables that were first recognized in México by Haro, Chavira and their colleagues at Tonantzintla. I recall discussions with Haro, in the 1950's, about whether a distinction ought to be drawn between these variables, which from the fact that the first discoveries were made in the Taurus dark clouds seemed to have some connection with star formation, and the ordinary dMe 'flare' stars in the field such as UV Cet. Since then, hundreds of these low-luminosity late-type stars have been discovered in and around dark clouds and H II regions. (Many papers on the subject are contained in the proceedings of IAU Symposium 137.)

In congested regions, spectroscopy of these stars is carried out most efficiently with a modern multi-slit system, as Carter & O'Mara (1991) have done in Orion. The 26 stars they observed have $\langle V \rangle \sim 15.5$. The mean extinction for the Trapezium region (Herbig & Terndrup 1986), $A_V = 2.4$ mag., is probably not appropriate for this particular sample which were purposely chosen to lie outside the bright nebulosity. If the $A_V = 0.2$ mag of Walker (1969) is used instead, it being an average over stars that mostly lie outside the Trapezium area, then the Carter-O'Mara sample have $\langle M_V \rangle \sim +7$. This is about 3 magnitudes brighter than expected for an early M dwarf on the ZAMS at that distance. Either these stars are pre-main sequence objects, or they are field dMe's in the foreground. With the exception of one TTS, the spectra reproduced by Carter and O'Mara do not differ in any obvious way from those of ordinary M dwarfs observed at that resolution.

This is a matter where the foregound interlopers have to be weeded out by a study of the proper motions, as Jones (1981) has done in the Pleiades, or by examining them for the Li I λ6707 line. Over 10^3 faint stars around the Trapezium region have been measured for proper motion by Jones & Walker (1988), but unfortunately none of the Carter-O'Mara stars are among them. An estimate of the fraction of interlopers can, however, be made in the following way. The Carter-O'Mara sample was drawn from the Haro & Chavira (1969) catalog of Orion flare stars, and 14 of these were measured by Jones and Walker. They are listed in Table 1.

The 4th column gives the membership probability assigned by Jones and Walker. Only 2 of the 14 entries are clearly non-members. If such a small fraction of interlopers is representative of the whole sample of Orion 'flare' stars, then contamination by foreground K and M dwarfs is minor, and one has to conclude that there is a large population of low-luminosity stars in the Orion Nebula, and I think it would be prudent to continue to call them 'flash' variables.

Table 1. Haro-Chavira Flare Stars Measured by Jones & Walker (1988)

Tonantzintla No.	JW No.	Parenago No.	Membership probability (%)	Variable designation	JW variable?
47	136+137	–	99.99	136=V551*	yes
50	178	P 1656	17	–	–
54	271	1748	99	V367	yes
59	900	–	99	–	–
63	968	2172	1	V569	no
64	972	2184	99	V570	no
65	985	–	99	V808	yes
67	998	2209	99	–	–
71	1017	2245	78	V379	yes
72†	1016	2246	88	OT	yes
74	1030	2270	99	OX	no
77	1049	2305	95	V578	no
159	907	2112	99	V803	no
230	971	2185	83	OR	no

* A close pair (2″) not resolved by Haro & Chavira; JW 136 is the southern component.
† T 72 is PC 326, the only star in this list that is also in the catalog of Tonantzintla Hα emission stars by Parsamian & Chavira (1992).

It will be interesting to see if this population, like the weak-line TTS, is detectable in X-rays. Clearly, Hα emission is not an effective means of discovery: only one of the 14 stars in Table 1 was also detected as having Hα emission on the Tonantzintla material. Emission at Hγ and Hδ is present in many of the stars Carter and O'Mara observed; they did not cover the Hα region.

It would be worthwhile to determine whether stars like these are spectroscopically distinguishable from the ZAMS dMe's of the solar neighborhood. If so, the transformation of one type to the other would be worth our attention.

REFERENCES

Backman, D.E., & Paresce, F. 1993, Protostars and Planets III, ed. E.H. Levy, J.I. Lunine, & M.S. Matthews (University of Arizona Press), p. 1253

Barsony, M., Schombert, J.M., & Kis-Halas, K. 1991, ApJ, 379, 221

Blitz, L. 1991, in Molecular Clouds, ed. R.A. James & T.J. Millar (Cambridge University Press), p. 49

Carter, B.D., & O'Mara, B.J. 1991, MNRAS, 253, 47

Churchwell, E. 1990, A&AR, 2, 79

______. 1991, Physics of Star Formation and Early Stellar Evolution, ed. C.J. Lada & N.D. Kylafis (Dordrecht: Kluwer), p. 221

de la Reza, R., Torres, C.A.O., Quast, G., Castilho, B.V., & Vieira, G.L. 1989, ApJ, 343, L61

Ghez, A., Neugebauer, G., & Matthews, K. 1992, Complementary Approaches to Double and Multiple Star Research, ed. H.A. McAlister & W.I. Hartkopf, PASP Conf. Series, Vol 32. (IAU Colloquium 135), p. 1

Golimowski, D.A., Durrance, S.T., & Clampin, M. 1993, ApJ, 411, L41

Gregorio-Hetem, J., Lépine, J.R.D., Quast, G.R., Torres, C.A.O., & de la Reza, R. 1992, AJ, 103, 549

Haro, G., & Chavira, E. 1969, Bol. Obs. Tonantzinta y Tacubaya, 5, 59

Herbig, G.H., & Terndrup, D.M. 1986, ApJ, 307, 609

Henning, T. 1991, Mem.Soc.Astron.Ital., 62, 887

Jones, B.F. 1981, AJ, 86, 290

Jones, B.F., & Walker, M.F. 1988, AJ, 95, 1755

Leinert, C., Weitzel, N., Haas, M., Lenzen, R., Zinnecker, H., Christou, J., Ridgway, S.T., Jameson, R., & Richichi, A. 1992, Complementary Approaches to Double and Multiple Star Research, ed. H.A. McAlister & W.I. Hartkopf, PASP Conf. Series, Vol 32. (IAU Colloquium 135), p. 21

Magnani, L., Blitz, L., & Mundy, L. 1985, ApJ, 295, 402
Mathieu, R.D. 1992, Complementary Approaches to Double and Multiple Star Research, ed. H.A. McAlister & W.I. Hartkopf, PASP Conf. Series, Vol 32. (IAU Colloquium 135), p. 30
Mendoza V., E. 1966, ApJ, 143, 1010
______. 1968, ApJ, 151, 977
Paresce, F. 1991, A&A, 247, L25
Parsamian, E.S., & Chavira, E. 1982, Bol. Obs. Inst. Tonantzintla, 3, 69
Peterson, C.J., & King, I.R. 1975, AJ, 80, 427
Reipurth, B., & Zinnecker, H. 1993, A&A, 278, 91
Roberts, M. 1957, PASP, 69, 59
Rucinski, S.M., & Krautter, J. 1983, A&A, 121, 217
Rucinski, S.M. 1992, PASP, 104, 311
Samuel, A.E: 1993, Thesis, Australian National University
Simon, M. 1992, Complementary Approaches to Double and Multiple Star Research, ed. H.A. McAlister & W.I. Hartkopf, PASP Conf. Series, Vol 32. (IAU Colloquium 135), p. 41
Simon, T. 1992, Seventh Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, ed. M.S Giampapa & J.A. Bookbinder, p. 1
Soderblom, D.R. 1991, Mem.Soc.Astron.Ital., 62, 939
Walker, M.F. 1969, ApJ, 155, 447
Whitmire, D.P., Matese, J.J., & Whitman, P.G. 1992, ApJ, 388, 190
Zinnecker, H., Brandner, W., & Reipurth, B. 1992, Complementary Approaches to Double and Multiple Star Research, ed. H.A. McAlister & W.I. Hartkopf, PASP Conf. Series, Vol 32. (IAU Colloquium 135), p. 50

DISCUSSION

Poveda: There are good reasons to think that the flare stars (UV Ceti stars) in the solar neighborhood are remnants of dispersed galactic clusters; in fact several of the known UV Ceti stars belong to the Hyades and Sirius superclusters, which are clearly dispersing. Hence we may conclude that those stars are just the older flash stars.

Herbig: Quite reasonable.

Rodríguez: I remember you mentioning the possibility of the structure in β Pictoris being due to a bipolar outflow. Do you care to comment on your present position on this issue?

Herbig: The best coronagraphic images of β Pic (Golimowski, Durrance, & Clampin, 1993, ApJ, 411, L41) still do not look to me like the outline one expects for an inclined circular disk. The original Smith-Terrile picture (of such a disk) continues to be defended very vigorously, however; see the review by Backman & Paresce (Protostars & Planets III, 1993). Perhaps this question will not be settled until the radial velocity test becomes possible.

Garrison: There are lots of stars in clusters and associations which have not been investigated, but for which there is evidence of circumstellar material. For example in Johnson's initial work on the ratio of total-to-selective absorption, he plotted the energy distribution vs. wavelength and extrapolated to infinite wavelength, these included lots of stars with circumstellar shells though they weren't recognized at the time. As far as I know, not many of these have been studied for the β Pic phenomenon.

George H. Herbig: Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822 U.S.A. e-mail: herbig@uhifa.ifa.hawaii.edu.