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THE EMERGENCE OF STELLAR ACTIVITY: T TAURI STARS

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RESUMEN. En esta reseña, se examina dentro de un contexto evolucionario el problema de la actividad estelar. Se dá una descripción breve de la evidencia observacional sobre la actividad en estrellas tardías y del origen más probable para esta actividad, el cual se considera que está en la distribución y magnitud del campo magnético. Se considera entonces la actividad observada en estrellas T Tauri, y se muestra que puede ser explicada con un modelo consistente con el usado en estrellas más evolucionadas. Estos argumentos y desarrollos teóricos recientes se usan para presentar un escenario evolucionario en el cual el agente de la actividad, el campo magnético, y su resultado, la actividad estelar, surgen como una consecuencia natural del colapso de una nube interestelar y cambian en el tiempo, a medida que la estrella evoluciona hasta llegar a los bajos niveles observados en estrellas de la secuencia principal. Desde esta perspectiva, las estrellas T Tauri representan el eslabón natural entre el medio interestelar y estrellas adultas.

ABSTRACT. In this review, the problem of stellar activity is examined into an evolutionary context. A brief description is given of observations related to activity in late-type main sequence stars and of the most likely origen for this activity, namely magnetic field strength and surface coverage. The activity observed in T Tauri stars is then considered, and it is shown that it can be explained with a model which is consistent with that appropriate for more evolved stars. These arguments and recent theoretical developments are then tied together to present an evolutionary picture in which the agent for the activity, the magnetic field, and its result, stellar activity, arise as a natural consequence of the collapse of an interstellar cloud and change with time as the star evolves to end up at the low levels observed in main-sequence stars. In this picture, T Tauri Stars constitute the natural link between the interstellar mediun and mature stars.

Key words; stellar activity, pre-main-sequence

I. INTRODUCTION

In this review, I will describe recent results on the problem of stellar activity from an evolutionary point of view. I will first examine briefly the activity observed in late-type main sequence stars, describing the most likely model for the origen of this activity. Then, I will refer to the activity observed in the stars which are predecessors of late-type main sequence stars, namely T Tauri stars, and I will present evidences that point to an origin for their activity that is consistent with that of more evolved stars. Finally, I will revise theoretical models that put the problem of stellar activity into a coherent evolutionary picture.

STELLAR ACTIVITY

Up to a few years ago, main sequence stars were thought to be well understood. Their observable characteristics were explained in terms of the usual conservation equations of the stellar structure, including radiation and convection as energy transport mechanisms. However, it was well known that in the sun there were regions were the traditional models of energy transport were not sufficient. In the solar chromosphere and corona the temperature rises up to a million degrees above temperatures around 5000K present in the photosphere. However, radiative equilibrium implies that $(dT/dr) < 0$, so that another mechanism of energy transport was required to explain the observed heating. Claims were made on the existence of regions similar to the solar chromosphere in the other late-type stars that showed emission cores in the Ca II K resonance lines (Jordan and Avrett 1972), but no global study was undertaken. With the advent of the ultraviolet satellites, specially IUE, and the recognition that UV spectra of late-type stars resembled that of the solar chromosphere in that they had lines of highly ionized metals, a fruitful line of research was open. Moreover, the detection of X-ray emission with the Copernicus and Einstein satellites in many late-type stars proved without doubt the existence of very hot gas in the atmospheres of these stars.

Schwarschild (1948) first suggested that the non-radiative heating of the solar chromosphere could be accomplished by sound waves created in the subphotospheric turbulent convection zone steepening into shocks as they traveled upward without appreciable loss of energy. Detailed calculations using the theory of Lighthill (1952,1954) and Proudman (1952) confirmed this hypothesis. Although nearly 90% of the energy transported is lost by radiation damping, the remaining energy is enough to heat at least the quite solar regions (De Loore 1970; Renzini et al. 1975; Schmitz and Ulmschneider 1981, and references therein). However, this explanation could not be simply applied to the case of all other late-type stars. In fact, Basri and Linsky (1979) observed a spread of a factor of 10 in observed emission in stars otherwise similar. Similar stars, according to the Vogt-Russell theorem, are expected to have similar convection zones in which the same power in sound waves would be generated, so that a dispersion of a factor of ten would not be expected.

In the sun, a close correlation is found between the magnetic field strength and the emission in Ca II K (Skumanich, Smythe and Frazier 1975). Now, the K line arises in the solar active regions, so this observation suggests that the magnetic field may be the agent for the activity in other stars as well. In fact, this suggestion is well confirmed in many grounds. Stein (1981) and Ulmschneider and Stein (1982) find that turbulent convection zones in the presence of magnetic fields can generate magnetohidrodynamic waves, which are up to a factor of 100 more efficient than sound waves in transporting energy to the atmosphere, since they are restricted to travel along the field lines. Also, late-type stars are expected to be rotating differentially due to the interaction between convection and rotation (Gilman 1979). In turn, the interaction of differential rotation and convection could amplify whatever magnetic field present inside the star, according to the dynamo mechanism (Parker 1970). According to these considerations, late-type stars may have magnetic fields on their surfaces, which would induce an efficient deposition of energy in their atmospheres, which in turn would result in heating and emission.

The theoretical expectations are confirmed by observations. Magnetic fields have been directly measured in a few active bright stars, and average strengths of a few KG have been found (Robinson 1980; Robinson, Worden and Harvey 1980; Marcy 1981,1984). On the other hand, binary systems of cool components show an anticorrelation between photometric and emission-line variability which could be interpreted in terms of rotational modulation of the light of spots and associated active regions (Baliunas and Dupree 1982; Marstad et al 1982). In addition, direct spectroscopic evidence for spots has been reported (Ramsey and Nations 1980). In the sun, spots are regions where the magnetic field strength is of 1-2 KG. These fields inhibit convection so less energy gets to the photosphere and the region is cooler than the surroundings. By extrapolation from the solar case, the indications of the existence of spots in other stars are indirect evidence for the presence of strong magnetic fields on their surfaces. Finally, a strong correlation has been found between the angular rotational velocity and the X-ray luminosity (Ayres and Linsky 1980; Walter and Bowyer 1981; Walter 1981,1982), the flux in the Ca II K emission line (Hartmann et al. 1984), and the flux in the g II k emission line (Noyes et al. 1984). Since according to the dynamo mechanism, higher otational velocity would result in larger magnetic field strengths, and therefore in larger mission, the observed correlations support the hypothesis of magnetic fields as agents of the ctivity in late-type stars.

In the sun, the magnetic field distribution is far from homogenous, in fact, the agnetic field is thought to be concentrated in tubes of constant magnetic flux of radius maller than 700 Km (Howard and Stenflo 1972; Frazier and Stenflo 1972; Tarbell and Title 1976). he density of magnetic flux tubes is different in different regions, been higher in spots and ctive regions. If a similar situation occur in other stars, then a different distribution of agnetic tubes among similar stars could explain the observed spread in emission characteristics Stein 1981). In fact, a magnetic coverage of up to 40% has been reported in very active tars (Robison et al. 1980), in support of this suggestion.

The evidences we have discussed so far seem to point to the magnetic field as the gent of stellar activity. Up to now, we have been concerned only with mature low-mass stars, lready in the main sequence. It is valid to ask at this point the question of the hystory of his activity. Are observations of stars in previous fases of evolution consistent with the odel for the origen of the activity in more evolved stars?. If this was so, then the model ould be more firmly supported. In the next section, we will review these observations.

CTIVITY IN T TAURI STARS

Some of the stars in this pre-main-sequence fase are the T Tauri stars. Stars dentified as T Tauri stars according to the traditional criteria (Herbig 1970) have masses ess or equal than 2.5 $M_{\odot}$ (Cohen and Kuhi 1979), and therefore would evolve into warm and cool ain sequence stars. They are characterized by a late-type optical absorption spectrum uperimposed by emission lines (Herbig 1962), infrared excess (Mendoza 1966, 1968) ultraviolet xcess (Walker 1972), ultraviolet line fluxes up to a factor of 10^4 higher than solar fluxes Giampapa 1984), X-ray luminosities of factor of 10^3 higher than solar, when detected Feigelson 1984), and highly irregular variability in lines and continua, with time-scales rom minutes to years.

Several models have been presented to explain the peculiar characteristics of Tauri stars. Some of these stars present inverse P Cygni type profiles on a few emission ines. Interpreting these profiles as evidence of infall of material, several authors have roposed that T Tauri stars are still in the phase of accretion of material from the nterstellar cloud from which they originated (Walker 1972; Ulrich 1976; Appenzeller and Wolf 977; Appenzeller and Bertout 1977; Bertout 1977; Mundt 1979). The emission, in this model, ould come preferentially from the region above the shock formed at the surface of the ydrostatic core corresponding to the central, more dense, regions of the cloud. The energy or the emission, on the other hand, would come from the kinetic energy of the accreting aterial. Several arguments can be given against the pure infall model. Cool shells of aterial ejected from the central object have been found in several T Tauri stars (Mundt 1983; oesgaard 1984). In addition, the surrounding molecular material shows evidence of motion due o the action of a stellar wind over it (Kutner et al. 1982; Edwards and Shell 1982; Calvet, antó, and Rodríguez 1983). The strongest emission lines, specially Hα, almost always show P Cygni-type profile, even in those stars which show inverse P Cygni profile in otherlines. inally, theoretical studies indicate that the optical depth of the envelope during the ccretion phase is so high that the stellar surface is not visible (Stahler, Shu, and Taam 980a,b,1981).

Alternative models have been proposed which are based in the solar analogy. In hese models, the emission comes from a dense, narrow region above the stellar photosphere, he chromosphere, and an extended expanding region, the wind. The energy for the emission, n analogy with other type of active stars, would come from the magnetic field, and ltimately, from the rotation of the star. These models assume an almost complete surface overage of magnetic fields, which induce both the activity and the expansion of material see reviews by Calvet 1983 and Hartmann 1984).

Several observational evidences support this model. Short-term variability in the U band can be interpreted as produced by a superposition of solar-type flares occurring continuosly over the surface (Worden et al. 1981) A similar interpretation in terms of flares can be given to the observed X-ray variability (Fiegelson and Kriss 1981, 1983; Montmerle et al. 1982; Fiegelson 1984). Several explanations have been given for the origin of solar flares (see, for instance, de Jager 1983), but all of them involve magnetic fields; again, based on the solar analogy, evidences for flares are indirect evidences of the presence and action of magnetic fields. In addition, the photometric variability in visible and red bands can be interpreted as due to the presence of spots on the surface, since the general trend is that the star gets redder when fainter at the observed bands (Herbst, Holtzman, and Klasky 1984).

A direct consequence of the assumption of high surface coverage of magnetic fields, once more based in the solar analogy, is a highly inhomogeneous surface. However, the models calculated so far have assumed homogeneity. Nonetheless, these models have had certain amount of success in reproducing observed characteristics. Theoretical models for the chromosphere, which assume hydrostatic equilibrium, can reproduce the visible continuum, the general characteristics of the absorption spectrum, and the flux in Ca II K. They can also produce the flux in Mg II k and Hα in the least active stars (Calvet 1981; Calvet, Basri, and Kuhi 1984). Deep chromosphere models cannot reproduce the infrared excess, which must come from a dust distribution around the star, nor the flux in Hα in the most active stars. The later must by produced in an extended expanding region, as would be expected in any case from the strong P Cygni profile this line shows. It is important that the temperature profiles determined for the chromosphere, that is for the innermost regions of the envelope of T Tauri stars, resemble those deduced for active solar regions, solar and stellar flares in that they have deep temperature minima and transition regions (Calvet 1983).

Alfven waves are expected to be created at the surface due to the existence of surface magnetic fields and body motions. As these waves travel upward, they deposit energy and momentum in the upper layers, creating a wind (Hartmann and MacGregor 1980). Hartmann, Edwards and Avrett (1982), using parameters appropriate to T Tauri stars, have been able to produce with this mechanism winds of strength of 10^{-9} to 10^{-8} $M_{\odot}$/yr, which is not unreasonable for T Tauri stars. The Balmer lines, and consequently, the Balmer decrement, produced in this wind region agrees with observations (Hartmann, Edwards, and Avrett 1982; Hartmann 1984).

Hartmann (1984) also finds that the Mg II k line comes primarily from the extended expanded region, while the Ca II K line is formed closer to the surface. The difference is mainly due to the lower transition probability of the K line and to the lower Ca abundance. This prediction is supported by the first simultaneous observations of the K and k lines in T Tauri stars. Cohen and Kuhi (1979) find a correlation between the emission line fluxes and the stellar luminosity. Although there is a large dispersion around the mean line, it is apparent from their Figure 17 that a line formed in the extended region as Hα has different dependence on luminosity that lines formed closer to the surface, like He I 5876 (Calvet 1984). Simultaneous observations of K and k, which refer to the same atmospheric structure, indicate that the Mg II k line has a dependence with stellar luminosity similar to that observed in Hα, while the Ca II K line shows no obvious dependence (Calvet et al. 1985). This could be explained if the k line originated in the wind region, while the K line formed near the surface and was consequently subject to the effects of the surface activity, in agreement with the predictions of the Alfven-wave driven wind.

The simultaneouly-observed fluxes in K and k suggest a separation of behavior relative to the mass (Calvet et al. 1985). Stars with masses higher than 1.5 $M_{\odot}$ have nearly the same k-line flux, while there is a correlation between k and K for the lower mass stars, which in turn appear to be the natural continuation in the K-k diagram of the correlation found for main sequence stars. Although the actual details are not understood at the present, this difference in behavior may be indicating that the stellar activity is due to magnetic effects in agreement with the model we are discussing. Indeed, according to the dynamo theory, two effects seem to be fundamental in determining the magnetic field strength and surface coverage, namely, the rotational velocity and the depth of the convection region

(Walter 1982; Paterno and Zucarello 1982). T Tauri stars with $M > 1.5\ M_{\odot}$ are already in the radiative track of pre-main-sequence evolutionary tracks (Cohen and Kuhi 1979), so that they have a radiative core and a narrow convection region (Iben 1965). Also, they posses substantial rotational velocity (Vogel and Kuhi 1981). On the other hand, T Tauri stars with $M < 1.5\ M_{\odot}$ are on the Hayashi track (Cohen and Kuhi 1979), and therefore and completely convective (Iben 1965). Also, at least the less active among them have rotational velocity less than 25 km s^{-1} (Vogel and Kuhi 1981).

Finally, a preliminary exploration seems to indicate that the energetic requirements could be accounted for, if the surface was almost entirely coverd by magnetic fields (Calvet and Albarrán 1984). If this is the case, then magnetohydrodynamic waves created in the convection zone could transport enough energy to the upper atmospheric layers to account for the minimum energy loss observed in T Tauri stars. Above this energy input, other phenomena as flares, which can deposit up to 10^8 to 10^9 erg cm^{-2} s^{-1} (Stein and Leibacher 1979) could account for the additional energy losses.

According to the arguments above, the activity observed in T Tauri stars is consistent with that observed in mature stars in that the magnetic field can be considered as the energetic agent, and an almost complete coverage of magnetic fields is expected. Following with our evolutive view, we ask now, how to explain the origen of this activity in even earlier stages?

FIRST STAGES

Stahler, Shu and Taam (1980a,b,1981) have calculated the evolution of a collapsing cloud of gas and dust up to the begining of the conventional quasi-static phase of pre-main sequence evolution of low-mass stars. As the collapse is non-homologous, the inner, denser parts collapse first creating a quasi-static core above which the rest of the cloud continues falling. In the surface of this core a shock wave is formed, which emits radiation that travels mostly to upper regions. The infalling material consists of gas and dust. Although at some distance from the surface the dust evaporates, the dust remaining in regions external to this radius is abundant enough to scatter and to absorb the radiation from inner regions. As the density in the envelope goes down, the optical depth in this dust envelope falls below one and radiation can escape. Thus, we can see only a "dust photosphere", roughly corresponding to the point where $\tau_{dust} = 1$ (Stahler, Shu and Taam 1980a, 1981).

Initially, when the temperature is less than 10^6K, the core is inert and because of the presence of the shock wave at the surface, the specific entropy increases outward. The core, therefore, is radiative. As the collapse continues and the temperature gets above 10^6K, deuterium reactions $^2H(p,\gamma)^3He$ begin, depositing energy, raising the temperature, and forcing the specific entropy to decrease with radius. A convective zone is thus created that soon covers almost all of the core interior. Besides this change, deuterium reactions play no other important role in evolution. It is then expected that even with a shock at the surface, the core will become convective at some stage.

If the initial cloud has a certain (but low) degree of rotation, the evolution of the central core is similar (Terebey, Shu, and Cassen 1984). In this case, the infalling material has a certain amount of angular momentum, and a disk is formed around the star. It is unlikely that the distribution of angular momentum of the material that does fall in the central core is such to produce uniform rotation. Rather, it is much more likely that as a result of the collapse, the core ends up with a strong differential rotation. We have here then a convective core rotating differentially, so we may expect that any magnetic field remaining after the collapse process be amplified by the dynamo mechanism (Shu and Terebey 1984). As the amplified fields raise to the surface, a large surface activity and eventually a wind will be generated. This serves two main purposes. On the one hand, it will stop the accretion of material. When this stops (simulated in the models by setting $\dot{M} = 0$), then the star readjusts itself in hours to have the structure of a star with the same mass in the Hayashi track. On the other hand, the wind "cleans" the enviroment, and the star, that is, the core appears with a large degree of surface activity. Stahler (1984) has calculated the "apparition" line in the HR diagram (simulating the effects of a wind by arbitrarily "turning off" the accretion at different times), and finds that this line coincides with the location in the HR diagram of the youngest, and most active, T Tauri stars observed. Thus, "the boisterous activity exhibited by young stars reflects the adjustment that they must make in reconciling the heritage they receive from the interstellar medium with the lifestyle they must persue as mature stars" (Shu and Terebey 1984). Although no detailed calculations have been made yet for these latter phases, the scenario appears very appealing. In particular, during the stage in which the wind begins to stop accretion, instabilities could be created which gave rise to the observed inverse P Cygni profiles, unifying after all the two apparently opposite models that have been proposed for T Tauri stars.

As the star evolves, the massive wind carries away angular momentum, rotational velocity thus decreases and so magnetic field strength and activity. The star tends to a state of minimum energy, that of uniform rotation. Evolution continues until the star becomes like the sun, with low rotational velocity, average magnetic field of 1 G, surface coverage of magnetic regions of less than 1%, only remnants of its splendour when it was a T Tauri star.

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