Evidence of Prominences on Cool Late-type Stars

P.B. Byrne[1], M.T. Eibe

Armagh Observatory, College Hill, Armagh BT61 9DG, N. Ireland

G.H.J. van den Oord

Sterrekundig Instituut, Postbus 80.000, 3508 TA Utrecht, The Netherlands

Abstract. We review the observed characteristics of co-rotating clouds of neutral hydrogen recently detected in rapidly rotating, chromospherically active late-type stars and commonly termed "stellar prominences". Their observed properties are placed in an overall interpretive framework and compared to standard solar prominences.

1. Introduction

Solar chromospheric phenomena are widely repeated among stars of solar spectral type and later. The corresponding stellar phenomena range in scale (physical dimensions, energy content, etc.) from a little less than solar to orders of magnitude greater. In general, at any given spectral type, this activity level correlates inversely with rotation period reflecting its origin in magnetic field energy generated via dynamo action. Thus starspots may occupy $\sim$10-20% of the stellar disk (Byrne 1996), while stellar flares release up to 10^6 times the energy of the largest solar flares (Byrne 1995).

Solar prominences are intimately associated with magnetic fields on the Sun (Tandberg-Hanssen 1995) and are characterised by cool (chromospheric temperature, i.e. $\sim 10^4$K) material embedded in the otherwise multi-million degree corona. They are seen as dark features in solar monochromatic images taken in chromospheric bright lines, such as CaII H&K or Hα, due to scattering of the underlying chromospheric radiation. Their projected areas are, in general, a small fraction of the area of the solar disk.

Stellar disks are not usually resolved. Therefore, the detection of solar-like prominences on stars presents severe observational difficulties. Nevertheless, recent investigation has indicated analogous structures on the most active late-type stars under favourable circumstances. A comparison of some important properties of four well studied examples of these stars are given in Table 1. The individual stars are discussed more fully in the sections which follow.

---

[1]Deceased, September 1997

Table 1.   Some parameters of prominence stars. Note that R_{Sp} is the radius derived from the star's spectral type (Allen, 1973).

Star	AB Dor	HK Aqr	BD+22°4409	RE1816+541
Spectral type	K0V	M1V	K5-7V	M1-2V
P_{rot} (dy)	0.517	0.431	0.424	0.459
$v\sin i$ (km/s)	91	69	60	61
$R\sin i/R_{\odot}$	0.93	0.59	0.50	0.55
$R_{Sp}/R_{\odot}$	0.89	0.60	0.65	0.57
$\sin i$	1.04	0.98	0.77	0.96

2.   AB Dor

Stellar prominences were first invoked to explain the Hα variations of the field K0V dwarf star, AB Dor (Cameron and Robinson 1989a, b). Absorption features were seen to cross the rotationally broadened Hα profile in times ∼1 hr from blue to red. Since this crossing time is very much less than half the rotation period of AB Dor (P_{rot}=12.4 hr) Cameron and Robinson concluded that they could not be due to surface features, e.g. plages or spots. Instead they invoked cool clouds of neutral hydrogen magnetically suspended high above the stellar photosphere and in forced co-rotation with it. When such clouds transit the stellar disk they scatter the underlying chromospheric Hα radiation giving rise to an absorption feature. The line-of-sight velocity of the resulting absorption reflects the velocity of the obscured portion of the stellar disk. Because the material is at least partially neutral and yet magnetically contained, the analogy with solar prominences is obvious.

Cloud height is related to disk crossing time and Cameron and Robinson's analysis of the crossing times for AB Dor suggested that these clouds lay at or above the co-rotation radius, i.e., the radius at which the centrifugal force equals the local gravity. They suggested that, as "normal" hot coronal loops evolve to larger radii, their apices eventually extended beyond the co-rotation radius and experienced reversed effective gravity. In a star such as AB Dor the co-rotation radius is very close to the photosphere (because of the rapid rotation) and magnetic fields are systematically stronger than solar, enabling loops to survive under these conditions. Pooling of material at the apex would then produce enhanced plasma density which could cool radiatively to produce the observed neutral material.

The condensed neutral material would be tied to the field lines only through collisions with the hot, ionised component and would eventually diffuse from it and disperse. The pressure of the hot gas in the loop legs would, however, continue to replenish the gas for some period. Cameron and Robinson pointed out that such a mechanism would remove angular momentum from the parent star. Their estimates of cloud masses and lifetimes suggested that these "coronal condensations" could be responsible for the rapid braking of young solar-type, rapidly rotating cluster stars which are thought to brake on a timescale of ∼10^8 yr (Stauffer 1987).

For some time however AB Dor remained a unique object. Further examples of rapidly rotating late-type stars should, in principle, exhibit similar

phenomenology.

3.   HK Aqr

HK Aqr is a rapidly rotating (P_{rot}=10.34 hr) early M dwarf in the field and, like AB Dor, its Hα profile is rotationally dominated. Byrne et al. (1996) made a detailed study of the behaviour of its Hα line and concluded that it too has disk-crossing neutral hydrogen clouds. Their analysis of cloud heights, however, suggested they were not at or beyond the co-rotation radius. Indeed, some of the clouds appeared to lie at altitudes more typical of large solar prominences. Thus, the condensation mechanism invoked by Cameron and Robinson could not operate in this case.

To make a more rigorous examination of allowed heights of the observed clouds van den Oord et al. (1998a, 1998b these proceedings) considered in detail the dependence of derived cloud height on all of the relevant parameters, i.e. stellar inclination, cloud latitude, etc. When applied to the observations of HK Aqr this analysis confirmed fully the earlier conclusions of Byrne et al. (1996) concerning cloud heights. How then are we to understand the earlier conclusions relating to AB Dor and the tendency for its clouds to occur near the co-rotation radius?

Van den Oord et al. pointed out the critical effect of stellar inclination on the range of allowed cloud heights. The smaller the inclination the less constrained cloud height is. Furthermore, relatively modest inclinations ($i \sim 60°$) resulted in cloud height being poorly constrained (Figure 1). They examined the supporting arguments for the inclination used by Cameron and Robinson ($i \sim 60°$) and concluded that a value of 90° was also acceptable, if not even more likely (Table 1). When this value of inclination was used, many of the clouds observed by Cameron and Robinson lay below the co-rotation radius (Figure 1b). Recent consideration of the value of AB Dor's inclination by Cameron and Foing (1997) also admits a value of 90°.

What of the mechanism for producing cool, neutral clouds in the absence of the co-rotation condensation effect? Van den Oord and Zuccarello (1998) pointed out that, cool apex loops can be created when coronal heating decreases at or near the loop apex. This can occur when a loop becomes stellar-sized and heating becomes less efficient.

Van den Oord et al. (1998a) also considered the balance of magnetic and mechanical forces on plasma in extended loops. They point out that, at larger distances, the low-level multipole active region fields resolve into a global field which is approximately dipolar. In this configuration clouds would be stable only near the equatorial plane and above a critical height unless there is a dip in the field lines. Below this critical height stability is impossible and material released from magnetic containment may flow along the dipole field lines towards the magnetic poles. Evidence for such a poleward flow of cool material should be sought in a rapid rotator with a high inclination.
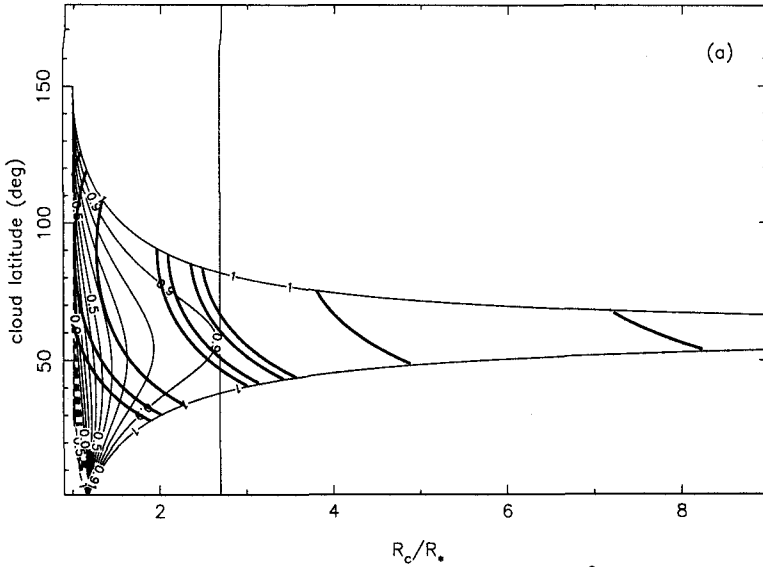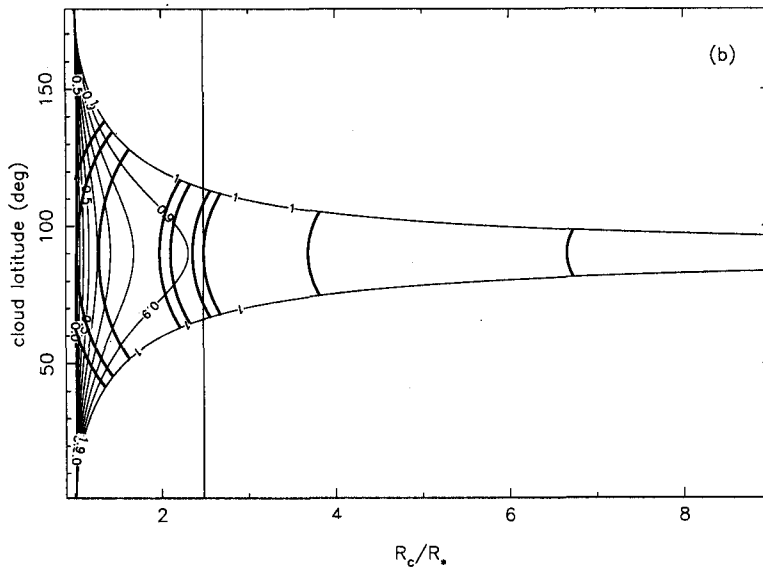
AB Dor clouds Gaussian fits for i=60°

AB Dor clouds Gaussian fits for i=90°

Figure 1.   Visibility diagrams for observed clouds on AB Dor for assumed inclinations of (a) 60° and (b) 90° (van den Oord et al. 1998a). The heavy lines represent allowed heights.
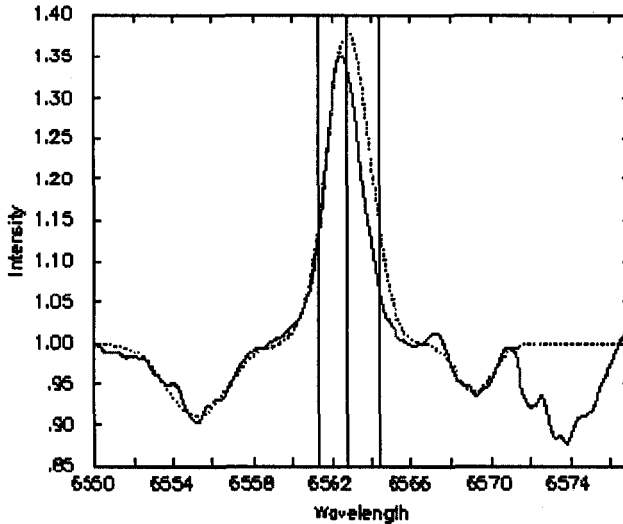
Figure 2.   Mean Hα profile for the K5V star, BD+22°4409 (Eibe et al. 1998a). The three vertical lines indicate the photospheric rest wavelength of the Hα line ±$v$sin$i$, while the dotted line is a symmetric profile constructed by reflecting the blue wing in the central wavelength.

4.   BD+22°4409

BD+22°4409 is such a star. It is a K5-K7 field dwarf which rotates with a period of ∼11.17 hr and $v$sin$i$ ∼60 km/s. Combining these two measurements suggests Rsin$i$ ∼0.5 R$_\odot$, considerably less than that expected for a ∼K6V star, and suggesting sin$i$ ∼0.77 (Table 1). Although the derivation of sin$i$ from $v$sin$i$ and rotational period, combined with radius from the observed spectral type, R_{Sp}, is subject to uncertainties in the determination of both $v$sin$i$ and R_{Sp}, it is probably accurate to ∼10%.

Eibe et al. (1998a) analysed BD+22°4409's Hα line seeking evidence of discrete clouds. Figure 2 shows the time-averaged Hα profile which results. It is displaced to the blue with respect to the rest velocity determined from photospheric lines and has a FWHM appreciably less than that expected from a uniformly bright star rotating with $v$sin$i$ ∼60 km/s. These anomalies are constant with time. We take this as evidence of continuous absorption on the red wing of Hα indicative of continuous inflow of neutral hydrogen as predicted in the van den Oord et al. scenario.

Taking into account the higher angle of inclination this is interpreted as evidence for cool material falling along the lines of the large-scale global field, originating either in regions where stability is not possible, or having diffused from closed field structures.
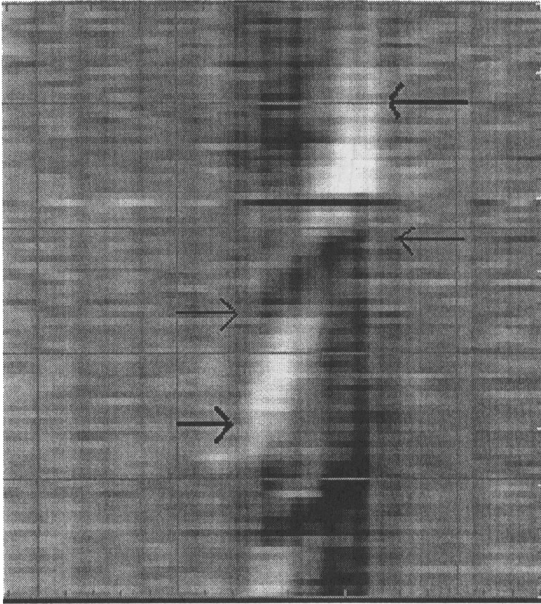
Figure 3.   Each line of the above image is a grey-scale representation of a single Hα spectrum of RE1816+541. The entire image is constructed from an entire night's data with time running from bottom to top. All have been ratioed to a mean Hα spectrum before display. Note the bright (emission) feature crossing the disk between the heavy arrows and the dark cloud intersecting it between the lighter arrows (Eibe et al. 1998b).

5.   RE1816+541

RE1816+541 is almost a duplicate of HK Aqr in terms of spectral type and rotation period (Table 1). Its Hα behaviour has been studied in detail by Eibe et al. (1998b). They found clear evidence for clouds similar to those around HK Aqr. Furthermore, they also recorded the passage of a plage-like, Hα-bright region across the stellar disk at or near the photosphere. The cloud passed over the plage region and absorbed it fully (Figure 3). This confirms nicely the fact that the clouds are indeed suspended above the stellar photosphere.

6.   Clouds in Other Stars?

Rapid rotation provides conditions in which individual clouds can be identified and tracked across a stellar disk. However, most active late-type stars are rotating too slowly to permit an approach similar to those described above. What would we expect to see when clouds transit the disk of an active slow rotator? Van den Oord et al. (1998a, 1988b these proceedings) have shown that, even in
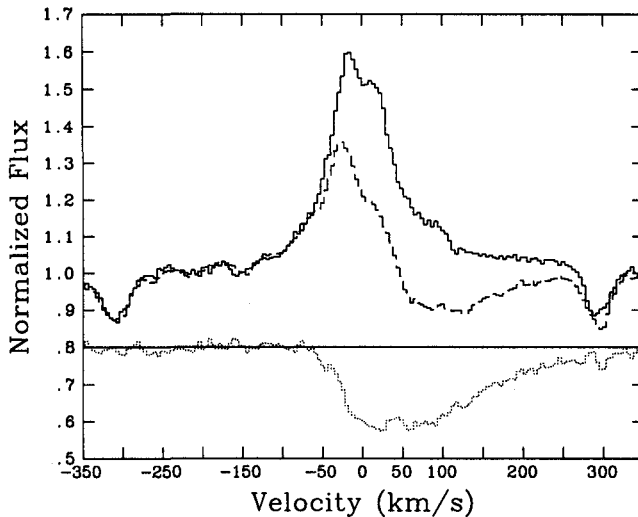
Figure 4.   Hα for the RS CVn star, II Peg, at two different epochs (Byrne et al. 1995).

the case of moderately fast rotators, all spatial resolution is lost for a wide range of cloud conditions. Thus all that will be seen in most cases will be short-term reductions in line flux.

If, however, there are flows present, due, for instance, to internal cloud motions or if one is viewing the star along a line-of-sight at high latitude, the symmetry of the absorbed line will be affected. Evidence of asymmetry in the Hα emission of active late-type stars has been remarked on. In Figure 4 we show both the mean Hα emission profile of the active RS CVn star, II Peg, and, superimposed, a type of profile which is seen from time to time. The mean profile is asymmetric in the sense that there is more flux to the blue side of line centre. Furthermore the reversal at line peak is similarly asymmetric. The dashed profile shows an almost unaffected blue wing while the red wing is massively cut away. Similar effects are seen in HeI λ10830Å (Byrne et al. 1998).

This gives the clear impression that all these asymmetries arise from the same root cause, i.e. absorbing material superimposed on the global chromospheric Hα emission, which is variable in its absorbing power. We interpret these phenomena as evidence for the existence of infalling neutral material similar in nature to that seen in the rapidly rotating late-type dwarf stars.

7.   Conclusions

The unique circumstances of extreme rapid rotation have aided the discovery of stellar analogues of solar prominences. However, as is so often the case, there are important differences between the phenomenon as seen in active stars and the solar case. These include scale, support mechanism and, probably, mass. Their

study is still in its infancy, however, and we look forward to rapid progress in the next few years.

References

Allen, C.W. 1997, Astrophysical Quantities, University of London Press

Byrne, P.B. 1995, in Flares and Flashes, Proc. IAU Coll. 153, (eds.) J. Greiner, H.W. Deurbeck and R.E. Gershberg, Springer-Verlag, New York, p. 14

Byrne, P.B. 1996, in Stellar Surface Structure, (eds.) K.G. Strassmeier and J.L. Linsky, Kluwer, Dordrecht, Holland, p. 299

Byrne, P.B., Panagi, P.M., Lanzafame, A.C., Avgoloupis, S., Huenemoerder, D.H., Kilkenny, D., Marang, F., Panov, K.P., Roberts, G., Seiradakis, J.H. and van Wyk, F. 1995, A&A, 299, 115

Byrne, P.B., Eibe, M.T. and Rolleston, W.R.J. 1996, A&A, 311, 651

Byrne, P.B., Sarro, L.M. and Lanzafame, A.C. 1998, in Cool Stars, Stellar Systems and the Sun, (eds.) J. Bookbinder and R. Donohue, ASP Conf. Ser., in press

Cameron, A.C. and Foing, B.H. 1997, Observatory, 117, 218

Cameron, A.C. and Robinson, R. 1989a, MNRAS, 236, 57

Cameron, A.C. and Robinson, R. 1989b, MNRAS, 238, 657

Eibe, M.T., Byrne, P.B., Jeffries, R.D. and Gunn, A.G. 1998a, in preparation

Eibe, M.T., Byrne, P.B. and Robb, R.M. 1998b, in Cool Stars, Stellar Systems and the Sun, (eds.) J. Bookbinder and R. Donohue, ASP Conf. Ser., in press

Stauffer, J.R. 1987, in Cool Stars, Stellar Systems and the Sun, (eds.) J.L. Linsky and R.E. Stencel, Lecture Notes in Physics, No. 291, Springer-Verlag, New York, p. 182

Tandberg-Hanssen, E. 1995, The Nature of Solar Prominences, Kluwer Acad. Publ., Dordrecht, Holland

van den Oord, G.H.J., Byrne, P.B. and Eibe, M.T. 1998a, A&A, submitted

van den Oord, G.H.J. and Zuccarello, F. 1998, A&A, submitted