THE ASTROPHYSICAL JOURNAL, 374:L55–L58, 1991 June 20

ROTATION AND EMISSION LINES IN STARS AND ACCRETION DISKS

KEITH HORNE
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
AND
STEVEN H. SAAR
Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
Received 1990 September 26; accepted 1991 April 5

ABSTRACT

In the accretion disks of quiescent dwarf novae, Doppler mapping studies reveal that Balmer emission lines increase sharply toward the center of the disk, with surface brightnesses scaling roughly as $R^{-3/2} \propto \Omega_{\rm Kep}$. Similarly, among chromospherically active stars the Hα and Ca II H and K emission cores are stronger in the more rapidly rotating stars, with surface brightnesses scaling again roughly as $\Omega_{\rm rot}$. Since in both cases the emission lines scale linearly with the rotation frequency, we propose that the mechanism powering the emission lines in quiescent accretion disks is the same as that in chromospherically active stars, namely the emergence of magnetic flux generated by the action of a dynamo, and its interaction with the atmosphere. If this empirical connection between disks and stars is in fact due to magnetic dynamos, the range of rotation rates available for testing dynamo theories expands from a factor of 10^3 to 10^7.

Subject headings: stars: accretion — stars: chromospheres — stars: dwarf novae —— stars: emission-line — stars: rotation

1. INTRODUCTION

Chromospheric activity in late-type stars, by analogy with the Sun, is thought to be a by-product of the emergence of magnetic flux which has been generated by dynamo action inside the star, and the interaction of this flux with the stellar outer atmosphere. Many dynamo models place the site of magnetic field generation near the lower edge of the subsurface convective layer. Investigation of the solar-stellar connection, which studies magnetic fields and related activity (e.g., chromospheric and coronal emission) in stars throughout the cool part of the Hertzsprung-Russell diagram ($T_{\rm eff} \lesssim 10{,}000$ K), has yielded great insight into the nature of the dynamo mechanism. The main optical spectroscopic signatures of chromospheric activity in stars are the emission cores seen in the Hα and Ca II H and K lines. More recently the Lyα, Mg II, and other lines in the ultraviolet, the He I D3 and 10830 Å lines, and the Ca II infrared lines have also been studied.

Cataclysmic variables, in particular dwarf novae in quiescence, have strong H I and weaker He I, He II, Ca II, and Fe II emission lines. These lines are typically double-peaked with wings extending to thousands of km s^{-1}, and their distinctive eclipse behavior shows that they form in a differentially rotating accretion disk encircling the white dwarf primary star of a close binary system. The origin of these disk emission lines is poorly understood. The Williams (1980) and Tylenda (1981) models of steady state LTE disks make emission lines at low accretion rates in the outer annulus of the disk, where the continuum becomes optically thin as temperatures drop below about 7000 K and H I becomes partially ionized. In more recent models accounting for vertical disk structure (Kriz & Hubeny 1986; Shaviv & Wehrse 1986; Mineshige & Wood 1990), viscous heating of the disk atmosphere gives rise to a vertical temperature inversion in the disk. Irradiation from the hot inner disk and boundary layer may produce a similar temperature inversion. So far, none of the models offers a natural explanation for the $R^{-3/2}$ emissivity law inferred from observed velocity profiles of the lines, nor has the precise source of the viscous heating in the disk atmosphere been identified.

Many of the emission lines which are signatures of magnetic activity in stars are also seen in quiescent accretion disks. This may mean nothing more than that similar physical conditions occur, for example, due to the radiative cooling curve of plasmas. But it prompted us to ask whether the emission-line excitation mechanism in stars and disks could be closely related. We show in this *Letter* that the line emission *follows roughly the same power law with rotation rate* in stars and accretion disks, suggesting that there may be a common excitation mechanism. This star-disk connection could greatly expand the parameter space available for testing dynamo theories.

Accretion disks are fertile ground for dynamo action. Keplerian orbits provide a strong shear which readily generates a strong toroidal magnetic field by amplifying any small radial seed field that may be present. Buoyancy leads to flux tubes rising out of the disk as their magnetic pressure approaches the gas pressure, and this will likely generate emission lines from disks just as it does in stars. All that is needed to sustain a dynamo is some form of feedback to regenerate the radial seed field. This feedback mechanism is not yet well understood, but internal waves (Vishniac, Jin, & Diamond 1990) or turbulence driven by the magnetic shear instability of Hawley & Balbus (1991) offer good possibilities. Shear and rotation rates in disks are much stronger than in stars, while densities are much lower and convective time scales much shorter, providing an opportunity to extend the study of dynamos, possibly into a new regime.

In this *Letter* we present empirical evidence which motivates the hypothesis that dynamo action plays a key role in generating emission lines from accretion disks. If true, then a comparison of X-rays, emission lines, variability, and other phenomena related to magnetic activity in both stars and disks will provide tests of dynamo theories over a wide range of parameters. In § 2, we present data from the literature in a way that allows us to compare emission lines of rotating stars with those of quiescent accretion disks. Implications for dynamo theories and suggestions for future extension of this program are briefly discussed in § 3.

2. AN EMPIRICAL CONNECTION BETWEEN DISKS AND STARS

Figure 1 presents a comparison of emission-line surface brightnesses as functions of rotation frequency for Ca II H and K emission in rotating stars, and for Hβ emission in accretion disks. Individual stars are represented by points and have rotation frequencies ranging from 10^{-3} to 1 cycles per day. For two different quiescent accretion disks we show the surface brightness dependence on disk radius, and hence on the local Keplerian rotation frequency ranging from 100 to 10^4 cycles per day, as determined by Doppler tomographic studies as described below. Comparison of the empirical data with the slanted lines indicates that in both stars and disks the surface brightnesses are roughly linearly proportional to rotation frequency, with a constant of proportionality that is a factor of 30–100 smaller for disks than for stars.

We have taken the stellar Ca II and rotation data largely from the extensive compilation by Rutten (1987). The raw fluxes have been converted to excess emission fluxes relative to the minimum emission flux seen in chromospherically inactive stars of similar color (Schrijver 1988). The observed excess emission-line flux is converted to a surface brightness using the distance and radius of the star as determined from its apparent magnitude, spectral type, and luminosity class (see Rutten 1987). Our sample includes both giants and dwarfs with spectral types of F or later.

In disks the emission-line surface brightnesses and Keplerian rotation frequencies have to be determined by a less direct method than that used for stars. The velocity profile of the line observed at a particular binary phase is an emission-weighted projection of the two-dimensional velocity field of the accretion flow onto the instantaneous line of sight. By observing the velocity profile at different binary phases, we obtain many different projections of the accretion flow, and from these projections we can reconstruct a two-dimensional map of the emission-line strength as a function of position on the surface of the accretion disk. This technique, known as Doppler tomography, has been developed for accretion disks by Marsh & Horne (1988). Doppler maps have been presented for the quiescent accretion disks in two dwarf novae: IP Peg (Marsh & Horne 1990) and U Gem (Marsh et al. 1990). Both systems are eclipsing and have well-determined binary system parameters, permitting accurate conversion of the Doppler maps to line emission as a function of disk radius, and hence Keplerian angular frequency, as plotted in Figure 1.

Note, however, that Figure 1 compares Ca II H + K emission in stars with Hβ emission in accretion disks. It would, of course, be better to use the same line in this comparison. Unfortunately, the Ca II H + K emission most widely observed in stars has not yet been mapped in disks because the large disk velocities blend these lines with the adjacent Balmer lines. Hβ has now been mapped in two disks but has not been widely observed in stars due to its relative weakness and the difficulty of properly extracting the chromospheric component of stellar Hβ profiles from the underlying photospheric absorption line.

Until future studies make more direct comparisons of stars and disk, we can only defend our comparison using different lines by noting that there is a good empirical correlation among different chromospheric emission lines in stars (e.g., Hartmann et al. 1984), with Ca II H + K being about 2.7 times the Hα line core emission in G dwarfs (Herbig 1985). Since both lines originate in stellar chromospheres, they should be roughly linearly proportional to each other and show similar dependences on Ω. In cataclysmic variables, the Hα/Hβ ratio ranges from about 0.8 to 2.0 (Echevarria 1988). Thus the points in Figure 1 might shift up or down by factors of 2 or 3 if the same line were to be used, and we must restrict our interpretation accordingly.

While Doppler maps are as yet available only for a few accretion disks, many more have been studied by modeling their emission-line profiles. Assuming the line emissivity to be a power law in radius, the velocity profile can be computed (see Smak 1969); its wings decrease with velocity roughly as V^{2b-5}. The power-law index b can thus be determined by fitting to the wings of observed emission-line profiles. Table 1 gives some of the measured power-law indices, which range from 1.5 to 2.25 in quiescent dwarf novae. Note that an $R^{-3/2}$ law was found for Hα emission from the accretion disk in the black hole binary A0620−00 (Johnson, Kulkarni, & Oke 1989), and for Paschen emission lines in SS 433 (Filippenko et al. 1988). These results indicate that an $R^{-3/2}$ dependence of emission-line surface brightnesses is a general characteristic of quiescent accretion disks.

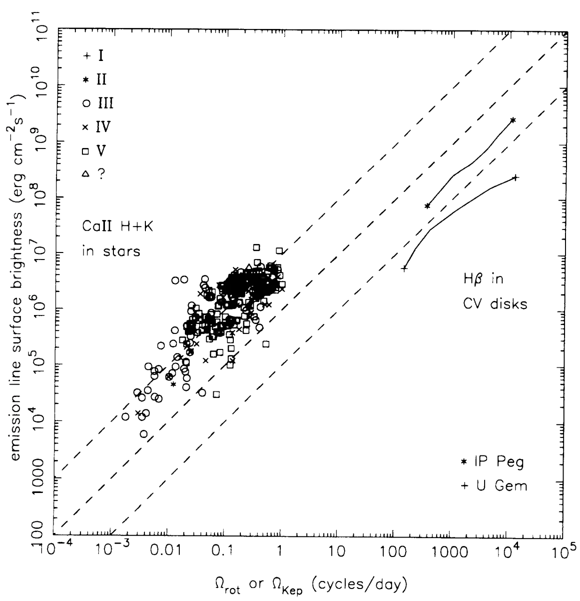

FIG. 1.—The dependence of emission-line surface brightnesses on rotation frequency among chromospherically active stars and within two quiescent accretion disks. For individual stars Ca II H + K emission-line surface brightnesses are plotted vs. the stellar rotation frequency. The plot symbols denote the luminosity class of each star. For the quiescent accretion disks, the Hβ emission-line surface brightness is plotted vs. the Keplerian orbit frequency, both of which increase from the outside toward the center of the disk.

3. DISCUSSION

We have discovered (Fig. 1) that emission-line surface brightnesses scale approximately linearly with the rotation frequency Ω for both a wide collection of cool stars *and* within several differentially rotating quiescent accretion disks. It is not surprising that emission lines increase toward the center of the disk, where more rotational kinetic energy is available.

TABLE 1

R^{-b} Emissivity in Accretion Disks

Star	Line	b	Reference
Z Cha	Hβ	2.25	1
	Hβ	1.7	2
HT Cas	Hβ	1.5	3
	Hβ	1.8	2
IP Peg	Hβ	1.8	4
U Gem	Hβ	1.5	5
SS Cyg	Hβ	2.2	2
A0620−00	Hα	1.5	6
SS 433	Pa12, 14	1.5	7

References.—(1) Marsh, Horne, & Shipman 1987; (2) Smak 1981; (3) Young, Schneider, & Schectman 1981; (4) Marsh 1988; (5) Stover 1981; (6) Johnson, Kulkarni, & Oke 1989; (7) Filippenko et al. 1988.

However, if a constant fraction of the rotational energy were being emitted, the emission-line strength should be proportional to Ω^2, rather than to Ω as observed. The similar scaling with Ω in stars and disks suggests that a common underlying mechanism is powering the emission lines: viz., the generation of magnetic fields by dynamo action and subsequent interactions of the fields to heat the ambient medium.

If our hypothesis is correct, then the range of parameter space available for testing dynamo theories is greatly expanded. The comparison of disks and stars expands from three to seven the number of decades in rotation frequency over which the dynamo can be gauged. In Figure 1 the linear relation over three decades in rotation frequency for disks and stars separately suggests that rotation is the primary parameter and that the dynamo (or at least its manifestation in the production of the Hβ and Ca II lines) is linear in the rotation frequency.

There is considerable theoretical support for the idea of dynamo action in accretion disks. Some sort of viscosity, usually parameterized as a factor $\alpha \times P_{\rm gas}$ (where $P_{\rm gas}$ is the gas pressure) is required to transport angular momentum outward (and material inward) in the disk. Densities in disks are believed to be too low for purely fluid-type viscosity to provide the required value of α, and thus investigators have turned to magnetic fields as a possible source of the viscosity (e.g., Shakura & Sunyaev 1973). A promising mechanism for generating turbulent viscosity in disks is the magnetic shear instability discovered by Hawley & Balbus (1991), which offers dynamical growth rates that are independent of the field strength for weak fields.

Both simple thin disk models (Pudritz 1981a, b) and more realistic thick disk models (Stepanski & Levi 1989) of turbulently driven dynamos predict a dependence of dynamo strength $\propto \Omega_{\rm Kep}$. The thick disk models also predict the presence of very localized, strong, temporally intermittent dynamo modes. These localized modes could explain the photometric flickering, complex time-variable line emission (Stover, Robinson, & Nather 1981) and rapid radio variability (Bastian, Dulk, & Chanmugam 1988) seen in disks: magnetic loops emerging buoyantly from the disk (Galeev, Rosner, & Vaiana 1979) could rapidly reconnect to heat the ambient gas in the accretion disk analog of solar/stellar flares. A quite different approach, which relies on internal waves in the disk to both transfer angular momentum and excite the dynamo (Vishniac & Diamond 1989; Vishniac, et al. 1990), also predicts both dynamo activity proportional to $\Omega_{\rm Kep}$ and the presence of strong localized modes. Thus, several reasonable models for magnetic dynamos in accretion disks exist which can broadly explain the observational results. We also note that the flattened geometry of disks may in some ways approximate the thin spherical shell in which most stellar dynamos are believed to operate (e.g., Gilman & DeLuca 1986).

Our hypothesis is founded on the observation of the roughly linear dependence of Ca II flux on rotation in stars. Clearly, however, this is not the whole story: the scatter among the stars and between the disks in Figure 1 is larger than experimental uncertainties, so secondary parameters must also be important in the generation of the emission lines. This fact has already been surmised by many previous stellar studies. In order to reduce the observed scatter, investigators have generally either modified the $F_{\rm Ca\,II} \propto \Omega$ relation with a stellar structure-dependent term (e.g., the convective turnover time, τ_C; Mangeney & Praderie 1984; Noyes et al. 1984), cast the relationship in forms which are linear only in limited parameter ranges (e.g., Marilli & Catalano 1984; Rutten 1987), or both (Simon, Herbig, & Boesgaard 1985).

To generalize, dynamos in stars at a fixed Ω may also depend on parameters such as the effective temperature, gravity, differential rotation rate, and the vertical structure of the star, in particular of the convective layers. In a Keplerian disk the parameters besides the local rotation rate which may influence the dynamo include the surface density, effective temperature, vertical gravity gradient, and irradiation. At a given rotation rate, these parameters may be different in different disk systems and some may change with time in a given system. We can begin to explore the role of these secondary parameters in stellar and disk dynamos. One common calibration of the Ca II flux–rotation relation sets $F_{\rm Ca\,II} \propto \tau_C \Omega$, the inverse Rossby number (Noyes et al. 1984). In a disk, the turnover time is probably something like $H/(\alpha C_s)$ where H is the disk thickness and C_s is the sound speed. Since in a Keplerian disk, $H/R = C_s/V_{\rm Kep}$, then $\tau_C^{\rm disk} = (\alpha\Omega)^{-1}$ and $F_{\rm Ca\,II} \propto \alpha^{-1}$. If α is constant with radius, as is often assumed, this obviously disagrees with the observations (Fig. 1). Thus, if we assume stellar and disk dynamos are similar, either α actually varies as Ω^{-1}, or the convective time scale is not a critical parameter for these dynamos. More detailed comparison of stars and disks may further guide dynamo theories by suggesting which of the possible secondary parameters are most important, and how the nature of the dynamo changes when they are varied. The differential rotation rates in disks, for example, are much better determined than in most cool stars.

The linearity of the stellar chromospheric activity–rotation relation in stars clearly *does* break down at high rotation rates ($\Omega \gtrsim 1$ day^{-1}) where $F_{\rm chromo}$ appears to reach a saturation limit (Vilhu 1984; Rutten & Schrijver 1987). This may be the result of a saturation in the dynamo generation of fields, in stellar surface coverage with flux tubes, or in the heating mechanism by which the magnetic fields transfer energy to the chromosphere. We do not yet know if a similar saturation level exists in accretion disk dynamos, but discovery of one would support our hypothesis.

In future work it will be important to explore more fully the empirical connections which may exist between chromospheric activity in stars and accretion disks. A good place to start would be Doppler mapping experiments in the Ca II H and K and infrared triplet lines of disks. The maximum entropy methods developed for Doppler tomography of disks (Marsh & Horne 1988) can be used to cope with deblending problems here. Another good candidate is Mg II λ2800 emission, which is also well studied in stars. (The other strong UV emission lines in cataclysmic variables, N v, Si iv, C iv, He ii, are thought to arise in a wind from the inner disk boundary-layer region between the inner disk and the white dwarf. This wind is believed to be too highly ionized to produce Balmer, Ca ii or Mg ii emission, and in any case, would not refer to dynamo related heating.) It might also be worthwhile to search for rapid, localized (in velocity) line emission enhancements which would be the signature of magnetic-related "disk flares," and to characterize their properties as a function of radius in the disk.

It should also be possible to bridge the gap between disks and stars by studying chromospheric emission from the secondary stars of cataclysmic variables. The secondary stars of cataclysmic variables have rotation frequencies in ranging roughly from 3 to 20 cycles per day, considerably faster than in the present sample of late-type stars. W UMa variables are also possible targets, with rotation frequencies of about 1 to 10 cycles per day.

We thank R. G. M. Rutten, J. E. Pringle, and R. Gilliland for comments on an early draft of the paper and A. Filippenko for a thoughtful referee's report. S. S. was supported by a Smithsonian Institution Postdoctoral Fellowship and NASA grant NAGW-112. K. H. was supported by NASA grants NAGW-1796 and NAGW-2264 and by the Space Telescope Science Institute Director's Research Fund.

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