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Evolved Stars: What Happens to Activity Off the Main Sequence

K.G. Strassmeier[1], F.C. Fekel[2], D.F. Gray[3], A.P. Hatzes[4], J.H.M.M. Schmitt[5], and S.K. Solanki[6]

1. Introduction

> *Now I understand why I am taking physics. Once a person understands how to turn the complex into the simple, the world becomes fascinating.* — (A student after seeing the Leonardo da Vinci exhibition in the Cambridge Science Museum.)

This is not an easy goal for a discussion summary with an attendance of approximately 100 astronomers though, and is even an impossible undertaking if only fragments of the comments were submitted by the participants. As you might have guessed by now, what follows is therefore more an inaccurate and mostly off-memory description of the discussed topics and somewhat biased towards the preferences of the panel members, i.e., the authors. However, original citations are included whenever available.

The present paper consists of three main sections, each covers one particular discussion topic: *Rotation regimes for evolved cool stars*, *Rotation-activity relations in the Hertzsprung-Russell Diagram*, and *Polar starspots.* Within each of these sections we start out with a summary of the respective 3–5 min introductions that were given by two of the panel members at a time: Gray and Fekel on rotation regimes, Schmitt and Strassmeier on rotation-activity relations, and Hatzes and Solanki on polar spots. These summaries are intended to identify problems and raise some uncomfortable questions that could be used as a starting point for discussion by the interested astronomers in the audience (or so we thought). The latter contributions are, naturally, only fragmentarily recovered, no on-line maximum-entropy voice decoder was available in the meeting room (do you hear, Andrea?) and we apologize if some valuable contribution didn't make it into the proceedings. Following our introductory talks are the discussion contributions by various astronomers in attendance. The respective speakers are identified in small caps type fonts. So lets see.

[1]Institute for Astronomy, University of Vienna, Austria
[2]Center for Automated Space Science and Center of Excellence in Information Systems, Tennessee State University, U.S.A.
[3]Department of Physics & Astronomy, University of Western Ontario, Canada
[4]McDonald Observatory, University of Texas, U.S.A.
[5]Max Planck Institut für extraterrestrische Physik, Garching, Germany
[6]Institute for Astronomy, ETH Zürich, Switzerland

2. Rotation Regimes for Evolved Cool Stars

2.1. Introductory Talks by D.F. Gray and F.C. Fekel

An H-R diagram published a few years back by Gray (1991, see Fig. 1) shows four potentially different sections where dynamos might have different characteristics. Stars that evolve across the top of the diagram increase their moments of inertia by a large amount, and therefore by the time they cross the Granulation Boundary, i.e., develop a convective envelope, most of them will have slowed their rotation below what is needed to drive a dynamo. Therefore most of the cool bright giants and supergiants would not be expected to have magnetic activity. These stars lie in the section labeled "Acoustic 1." But when they were on the main sequence, these stars likely had a Maxwell-Boltzmann distribution of rotation, and so there should be a few of them from the high-velocity tail of the distribution that are still rotating fast enough to generate magnetic activity. Is this picture in accord with the fraction of stars showing X-ray emission?

Stars starting near the center of the main sequence will evolve across the Granulation Boundary and then the Rotation Boundary. Temperature inversions are seen to start building in strength as soon as the stars cross the Granulation Boundary but before they have strong magnetic braking. This is the "Magnetic 1" domain. Do these stars have a different type of dynamo running initially (Gray 1992), Or is the temperature inversion driven completely by non-magnetic mechanisms? Or is it just that the magnetic field is too weak to generate significant braking? Or maybe there are simply no open field lines yet. As soon as these stars evolve across the Rotation Boundary, strong magnetic braking takes away much of their angular momentum, at least in the envelope, and then we have magnetic activity generated by relatively slowly rotating stars. This is the section termed the "Magnetic 2" regime. Now according to Gray, there shouldn't be any fast rotators in this section, except, of course, for tidally coupled binaries, but Fekel and collaborators repeatedly showed that there are some apparently single rapid rotators that do appear here (listed in Table 1). What are these objects? Fekel offered two explanations that have been in the literature for a while: 1) the stars are coalesced binaries or, 2) they somehow maintained a rapidly rotating core and have angular momentum transfered to the surface layers when they evolve off the main sequence. If core angular momentum is dredged up to the surface, the dynamo and magnetic braking should restart according to the rotostat hypothesis of Gray (1991).

Stars starting out on the main sequence below about F5–G0 will suffer significant rotational braking before leaving the main sequence. They go directly into the Magnetic-2 regime with rotation rates somewhat slower than their more massive relatives. Can these lower-mass stars be identified in any way? Is their magnetic activity or the structure of their temperature inversions any different from the rest of the stars in this regime?

As evolution continues, the moments of inertia can be expected to increase, and stars in the Magnetic-2 portion will slow down even more. When we were sure we had a Coronal Boundary, D.F. Gray proposed this as the mechanism for it, namely that rotation became too low to support magnetic activity and we were back to non-magnetic excitation in the domain labeled "Acoustic 2" on the cool side of the Coronal Boundary. Now we seem to have detections of

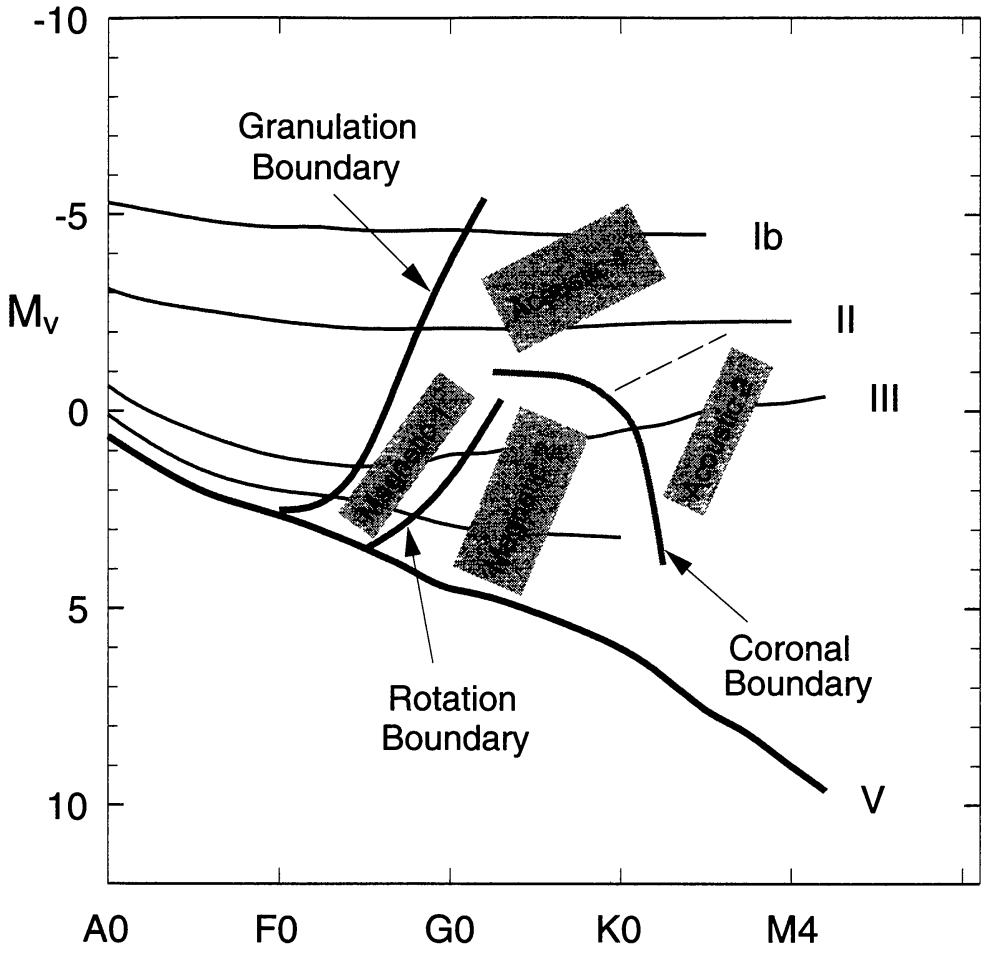

Figure 1. The magnetic and acoustic domains are indicated in this H-R diagram along with the usually referred boundary lines. (Diagram supplied by David F. Gray, University of Western Ontario.)

X-rays in the acoustic regime and the question is: are these rapidly-rotating tidally-coupled binaries? Are they single stars that somehow have saved enough rotation on their own to drive a more-or-less normal $\alpha\Omega$ dynamo? Is there some other dynamo process acting here, one that requires little or no rotation? Is there some non-dynamo process occurring that can give the observed X-rays? Shock waves? Pulsations?

Another particular question raised by Fekel is where did the lithium of these rapidly-rotating, single giants come from. The Li-survey of Brown et al. (1989) showed 4% out of 644 slowly-rotating giants with a $\log n(\mathrm{Li})$ greater than 1.3 while an updated version of the survey of Fekel & Balachandran (1993) found 9 out of 19 rapidly-rotating giants with that abundance. If we understood how primordial lithium is mixed in coalesced binaries, we could differentiate between the two scenarios. Do we then expect the dynamo to be the same? Table 1 is

a list of rapidly-rotating single giants, effectively single giants, i.e., components in very long period binaries, and the four presumed FK Comae stars.

Table 1. Rapidly rotating single (and effectively single) giants

Star	V (mag)	$B-V$ (mag)	Sp. Type	M_V[a] (mag)	$v \sin i$[b] (km/s)	$\log n$(Li)
HD 9746	5.92	1.21	K1 III	0.37	9.0	2.8
HD 11150	7.06	1.16	K2 III	0.90	16.2	1.2
HD 17144	8.22	1.19	K1 III	1.11	21.3	1.1
HD 18645	8.01	0.75	G5 IV	2.71	9.8	<0.1
HD 31993	7.50	1.28	K2 III	0.62	33.4	1.4
HD 33798	6.99	0.95	G8 III	1.75	33.1	1.5
HD 34198	6.91	1.12	K0 III	0.60	16.8	0.4
HD 37434	6.08	1.17	K2 III	0.06	49.7	<0.1
HD 72146	7.35	1.22	G8 III	1.05	17.4	1.4
HD 203251	7.98	1.22	K2 III	...	46.5	1.4
HD 233517	9.72	1.32	K2 III	...	18.0	>3.0
HD 51066	6.99	1.04	K0 III	0.21	45.6	1.5
HD 152178	8.55	1.04	K0 III	0.18	28.8	0.7
HD 160538	6.55	1.05	K0 III	1.48	6.7	<0.3
HD 218153	7.62	1.12	G8 II	1.25	28.9	<0.8
HD 32918	8.06	1.08	K1 III	0.74	45.	1.1–1.6
FK Com	8.14	0.88	G8 III	1.29	160.	...
HD 199178	7.24	0.76	G5 III-IV	2.38	67.	...
1E1751.0+7046	9.64	1.10	K0 III	...	23.0	1.8

[a] M_V from *Hipparcos* parallax
[b] Fekel 1997

2.2. Discussion

Peter Ulmschneider: Could you put up that viewgraph of your rotation regimes again? You see a huge section where you label it Acoustic 1, and I think maybe "acoustic" is not the right word. Acoustic waves usually have high frequencies, frequencies above the atmospheric cut-off. Other waves arise with pulsation and have periods much larger than the acoustic cut-off period. Now I think there is something missing in all of these things, and nobody has so far worked it out, and I think it would be very nice to have someone work it out because in the Sun we have these five-minute oscillations. These oscillations in higher luminosity stars could turn into shocks, heat the higher atmosphere and possibly generate X-rays.

Jürgen Schmitt: Yes, but in Mira-type variables you get much slower velocities, and these won't produce X-rays.

Peter Ulmschneider: ... but we should include the lithium aspect of the picture. (Klaus says something, people laugh... must have been good).

Tom Ayres: What percentage are the rapid rotators among the whole population of K giants?

Frank Fekel: It depends on what you call rapid rotation. My guess would be about 1% of the late-G and K giants have projected rotational velocities ≥ 5 km s^{-1}.

Tom Ayres: (puts up a H-R diagram demonstrating the "coronal graveyard" and discusses it.)

Luca Pasquini: I'm sorry I didn't bring any view graphs ... There are two stars in your H-R diagram that both are binaries, both have very strong X-ray (or IR??) emission, and there is no way to put them there.

Tom Ayres: Red giants might have "buried" coronae. Hertzsprung-gap giants might have relic large scale "magnetospheres" that are destroyed at ≈G0 by the rapidly deepening convection zone.

Ed DeLuca: I don't think anybody has difficulty generating magnetic fields in convection zones. I mean, dependence on rotation is up in the air, but it doesn't have to be rotating quickly in order for you to have a medium that is very attractive for generating magnetic fields. If you didn't generate magnetic fields in a turbulent convection zone, you would have a hard problem. So generating magnetic fields in highly conducting material that has turbulence is not a problem. The thing nobody is going to be able to tell you is what is the amplitude of the field. How does the field saturate? All of those questions we don't know for the Sun, and we don't know them for anything else either. And we don't know its dependence on shear, and you come up with all sorts of ad-hoc models that terminate and look like solar. But we don't actually know what the physics is that is going to saturate the magnetic field. So a transient magnetic field on these things is not a problem.

Andrew Collier-Cameron: It's nice to see that the *Hipparcos* parallaxes for the single, rapidly rotating K giants put them on evolutionary tracks for stars of ≈2 $M_\odot$. Their progenitors will then have been radiative and not subject to significant magnetic braking, *or* lithium destruction in their surface layers, on the main sequence. I looked at the luminosities of 18 of these stars a few years back, and found that their radial velocities showed a very small scatter about the local standard of rest values — consistent, in fact, with ages of order the typical A-star lifetime. It would be worth using their Hipparcos proper motions now to do it properly. And does anybody know how long it takes for a 2 $M_\odot$ subgiant/giant to deplete its surface lithium to values below those observed?

Antonio Maggio: We have problems to understand not only the high-velocity, high-lithium giants, but also the behavior of apparently "normal" clump giants (as strongly suggested by the low Li abundances and typical "evolved" C/N abundance ratios) which have low surface rotational velocities but very high magnetic activity (measured e.g., by X-ray luminosity). Examples are the K III stars β Cet and the Hyades members θ^1 Tau and γ Tau. For these stars the surface rotation *and* the evolutionary stage (i.e., age) are not sufficient to predict their activity level. In fact, among the late-G and early-K giants we observe a spread of about three orders of magnitude in X-ray luminosity which cannot be simply accounted for by mixing of single and binary stars, or first-crossing and clump giants. One of the missing ingredients might be differential rotation and in particular the radial rotation gradient which is part of $\alpha\Omega$ dynamos. This parameter ($\nabla\Omega$) may be especially important for stars which experience substantial changes of their interior structure, i.e., during post main-sequence evolution.

Noam Soker: We must consider the role of planets and brown dwarfs on the evolution of evolved stars. About 5% of solar-like stars were detected to have close (≤ 1 AU) and massive ($\geq 1\ M_{\rm Jupiter}$) planets. [Note from the authors: this finding comes from the study of asymmetries of planetary nebulae rather than direct detections.] I estimate that many more will be detected to have planets at $d \leq 5$ AU and down to 0.1 Jupiters. These planets will be engulf by RG and AGB stars despite their orbital angular momentum and gravitational energy. The star, thus, will be spun up and its mass-loss rate will increase. These effects may also account for the second parameter of the horizontal branch.

Peter Ulmschneider: Planets can be very close (see 51 Peg) and likely deposit a lot of energy in the envelope of the star.

Suchitra Balachandran: ... but in addition to that, we now find stars that have equilibrium values of lithium, and sometimes higher than equilibrium values.

Klaus Strassmeier: Could it be that all of these rapidly-rotating K giants with high lithium abundances actually display low-amplitude radial velocity variations like the ones Artie Hatzes was describing in his talk? Presumably either due to some very low-mass companion, a brown dwarf or a super-Jupiter, or due to non-radial pulsations?

Frank Fekel: It's certainly possible. My velocities from KPNO for the single rapidly rotating giants have typical precisions of 0.3–1.0 $\mathrm{km\,s^{-1}}$, depending on the extent of spottedness and the line broadening. Mean velocities listed for many of those stars in Fekel & Balachandran (1993) have standard errors of the mean of 0.1–0.4 $\mathrm{km\,s^{-1}}$. Thus, the typical stellar companions we ordinarily think about can be eliminated, especially those with periods as short as a couple weeks or a few days. Any companion would have to be a very special kind of object.

Jeffrey Linsky: On the topic of the bright giants and supergiants, once they have gone through a dredge-up cycle the interior structure of the star has changed.

Andrea Dupree: We did a survey of calcium H&K fluxes up the red giant branch including clump giants, and clump giants are not any different from the regular giants going up the red giant branch. We went below the clump even, and there is a nice smooth decrease of calcium K. There is also no rapid break, no spin-down as predicted by theory, so something different is going on. Cluster stars are the best sample to study activity. The M 67 giants show smooth variations, with $B-V$ color along, irrespective of whether the star is a clump giant, below the clump, or on the RGB. So whatever the process, there does not seem to be a discontinuity when helium burning starts.

3. Rotation-Activity Relations in the H-R Diagram

3.1. Introductory Talks by J. Schmitt and K. G. Strassmeier

The existence of transition regions and coronae in many late-type giants was recognized almost twenty years ago when the first observations of C IV emission with *IUE* and soft X-ray emission with the *Einstein* satellite were made. One of the first and most important findings was the establishment of a so-called

dividing line in the UV-emission (e.g., Linsky & Haisch 1979) and X-ray emission (Ayres et al. 1981), that separates the "coronal" yellow giants from the "cool" red giants. The position of this dividing line in the HR diagram as well as its physical interpretation has been the subject of many papers.

Two recent developments are expected to significantly impact on our understanding of activity off the main-sequence: First, finally *Hipparcos* parallaxes are now available for almost all giants brighter than 6.5 magnitude; this means in particular, that complete volume-limited samples of such stars can be accurately constructed. And second, a flux-limited X-ray survey of giants is now available (e.g., Hünsch et al. 1998). The sensitivity of the observations is such that stars with X-ray emission above $L_X \sim 10^{29}$ erg s^{-1} can be detected within 100 pc. Further, volume-limited X-ray samples of giants are available reaching sensitivities of solar maximum X-ray luminosity at a distance of 25 pc.

Given these new data, we pose three questions for our discussion:

1. Is there an onset of convection also among giants and where is it located in the HR-diagram?

   Adopting the "canonical" view that the main sequence progenitors of the now observed giants were B- and A-type stars, which survived their main-sequence existence without any angular momentum loss, one would expect the onset of activity once the stars develop significant convection zones similar to what is seen on the main sequence. Is there any evidence for this in the data? Is the X-ray emission one sees from F-type giants of magnetic origin?

2. What is the nature of the X-ray dividing line?

   Looking at the HR diagram with the X-ray detected giants (Fig. 2), one gets the impression that X-ray emission is found for all types of stars. How does one explain the emission of the few detected M-type giants? How about the hybrids, all of which seem to show X-ray emission? Do stars actually "cross" the dividing line?

3. In the HR diagram one finds high activity stars ("β Ceti like") next to low-activity stars. Can the observed X-ray activity be linked to the mass and the evolutionary status of the stars in any sensible way?

   As is abundantly known, the nature of stellar evolution leads to a crowding of stars of different masses and different evolutionary status in the HR-diagram. Obviously, higher mass giants and lower mass giants must have had a rather different activity history on the main sequence. Similarly, first time crossers and clump giants might be different in their activity properties.

Chromospheric activity in evolved stars still remains quite unexplored, despite all the attention given to magnetic activity of solar-type main-sequence stars. In a recent study of Ca II H and K emission in evolved G and K stars (III, III–IV, and IV), Strassmeier et al. (1994) found that surface fluxes are scaled linearly with stellar rotational velocity and that the flux from the cooler giants ($T \leq 4500$ K) depends stronger on rotation than the flux from the hotter stars ($T \geq 5500$ K), in agreement with previous findings for main-sequence stars.

However, large scatter in these rotation-activity relations indicates that rotation is not the only relevant parameter and is suggestive of a more efficient connection between magnetic-flux generation and rotation in the cooler stars. This, at least, would indicate a similarity to the main-sequence dynamo. When does this similarity break down? Are the slowly rotating AGB stars obeying a diminished rotation-activity relation, if at all? Or is the temperature dependence seen for giants masked by some other parameter that is not so important while still on the main sequence?

3.2. Discussion

Antonio Maggio: We have performed a survey of 1–3 $M_\odot$ stars evolving off the main sequence, falling in pointed *ROSAT*/PSPC observations (see poster by Pizzolato et al.). We have divided stars in two mass ranges according to *Hipparcos* parallaxes and up-to-date evolutionary tracks. We have found (1) M <1.5 $M_\odot$ stars (F and G on the main sequence) are in general low X-ray emitters ($L_X < 10^{29}$ erg s^{-1}), (2) for the 1.5 < M < 3 $M_\odot$ stars (A type on the main sequence) there is a trend of increasing L_X with $B-V$, i.e., age, up to $B-V$ ≈0.8; in the same $B-V$ range (the Hertzsprung gap) there are also a number of stars (≈ 10%) with relatively high X-ray emission levels ($L_X > 10^{30}$ erg s^{-1}). Are these stars progenitors of the high L_X stars like β Ceti? Finally, for $0.8 < B-V < 1.0$ there is a large spread in L_X (3 dex) which could be due only in part to mixing of first crossing and clump giants.

Matthias Hünsch: (short presentation) I would like to present some plots concerning X-ray emission from late-type giants. We have searched the Bright Star Catalog (BSC) in the data of the *ROSAT* all-sky survey and detected 450 stars [see Fig. 2]. This figure shows all detections (asterisks) over-plotted all BSC stars from Hipparcos data. It can be seen that there is virtually no region in the HRD, where stars exist but no X-ray emission may be found. My conclusion is, that the X-ray dividing line does not exist and that there is only a gradual decrease of X-ray luminosity toward later spectral type. Of course, in many cases — like the M giants — it still has to be clarified whether these stars are binaries. However, the M-type giants are quite old (≈1 Gyr) and it would be difficult for a main-sequence companion of the same age to produce the observed X-ray luminosity, i.e., ≈ 10^{30} erg s^{-1}. While the F-type giants show quite uniform X-ray luminosities of typically 10^{29} erg s^{-1}, we observe a large spread in L_X for the clump giants. This may be caused by stars of different mass and evolutionary status populating the same region of the HRD or an intrinsic spread of angular momentum already on the main sequence which might reflect later on in the giant stage as well. We also do know very little about activity cycles in giants and I wonder whether giants might also fall into some sort of Maunder minimum. We can also see a general decrease of X-ray luminosity with decreasing stellar mass, as already mentioned by Antonio Maggio.

Klaus-Peter Schröder: We can see that *all* near single giants (d ≤35 pc) with deep *ROSAT* pointings in the K-giant clump area have some X-ray activity! Most of them — due to the life-time ratio — must be He burning, except one or so being first time crossers. This raises the question, how can the energy source of stellar activity (rotation?) survive the top of the giant branch? There

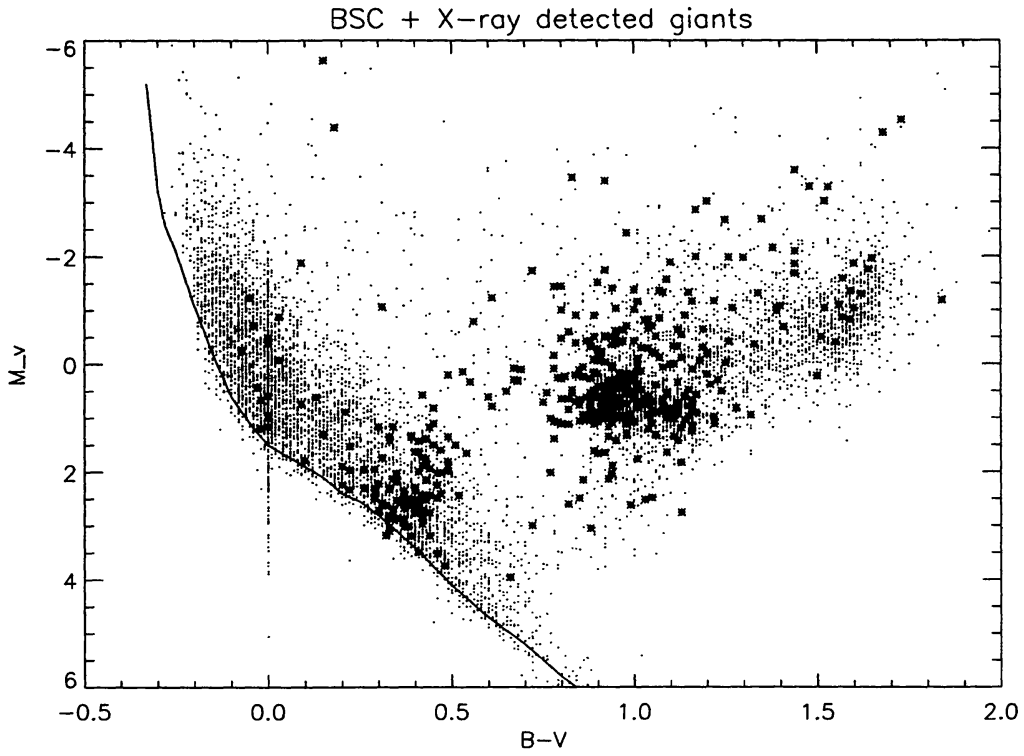

Figure 2. X-ray detected giants of spectral type A to M in the H-R diagram (asterisks). Dots are all Bright-Star-Catalog stars with data from *Hipparcos*. A total of 450 objects was detected in the *ROSAT* all-sky survey. (Diagram supplied by Mathias Hünsch, MPE.)

is also a dependence of mass and evolutionary history that, however, is easier to understand: mostly X-ray luminous hybrid stars are roughly the more massive the more X-ray luminous. The only nearby non-detected giants are evolved up the AGB and of low mass ($\leq 1.5\ M_\odot$). The more mass the later the star got into having a convection zone and the later stellar activity got switched on.

Matthias Hünsch: In the *ROSAT* all-sky survey we have found a couple of F-type bright giants (e.g., Canopus, a F0 II star) and we have also some deep pointings on F-type supergiants; all of them turned out to be X-ray sources. However, Gray's granular boundary is located at early G types among the supergiants. Therefore, F-type supergiants should lack outer convection zones and consequently magnetic activity. It is puzzling how such stars could have X-ray luminosities of $\approx 10^{30}$ erg s^{-1} or more as observed by *ROSAT*.

David Gray: But remember that stars on the hot side of the granulation boundary do show strong line asymmetries indicative of significant photospheric velocity fields. There may be other X-ray generating mechanism at work here.

Peter Ulmschneider: Concerning X-rays in stars beyond the Linsky-Haisch line which apparently are not members of binary systems. These stars have increased their radius considerably. Maybe one has to think about envelopes which suddenly engulf planets, e.g., a Jupiter-like planet close to the star. It would be

interesting to see if the bow shock of such a planet orbiting in the stellar envelope could produce enough X-ray luminosity.

Jürgen Schmitt: (Note from Jürgen Schmitt: This is now "unfair" since I used my privilege as coauthor and added the following when putting together the manuscript, so this response was not directly made to the above remark.) I took some of the better known planets, calculated their kinetic energies (the gravitational energy is essentially the same), assume that this kinetic energy is completely converted into X-ray emission (which is bold since the orbit velocities are rather low), and compute the time scale (in years) over which such a process could sustain an X-ray luminosity of 10^{29} erg s^{-1} (which actually is on the low side for active giants). Looking at the numbers in Table 2, I conclude that, first, only Jupiter-size planets matter, and second, that this process can operate only during a relatively short time (if at all).

Table 2. Maximum hypothetical "X-ray life times" for planets

Planet	Mass (g)	$v_{\rm orb}$ (km/s)	$E_{\rm kin}$ (cgs)	$t_{\rm life}$ (years)
Mercury	3×10^{26}	47.9	4×10^{39}	1,200
Venus	5×10^{27}	35.1	3×10^{40}	8,500
Earth	6×10^{27}	29.8	3×10^{40}	8,500
Jupiter	2×10^{30}	13.1	2×10^{42}	1,000,000
Saturn	6×10^{29}	9.6	3×10^{41}	84,000

Axel Brandenburg: As Ed DeLuca has been saying earlier, there is always the possibility of a small-scale turbulent dynamo that would contribute to heating the X-ray corona. So, even when $\Omega \to 0$ the X-ray emission should not vanish.

Klaus-Peter Schröder: The mass-dependence of the X-ray luminosity may hint that rotation is in some way important in the maintaining of stellar activity until the AGB. But only a few percent of the total mass may survive in the small non-convective core as it is on the top of the giant branch.

Jeffrey Linsky: Magnetic and chemically peculiar B stars are X-ray emitters but the stars have no convection zone. So I conclude that X-rays are emitted when magnetic field lines are stressed either by convection (in the cooler stars) or by winds (in the B stars) or by other means.

Thomas Berghöfer: Utilizing the *ROSAT* all-sky survey, Berghöfer et al. (1997) studied the X-ray properties of bright OB stars. Among the supergiants we found no credible evidence for X-ray emission of stars later than spectral type B1. Early-type star X-ray emission is produced by strong shocks in the radiatively driven winds and generally obeys the relation $L_{\rm X}/L_{\rm bol} \approx 10^{-3}$. The dividing line for hot supergiants placed at spectral type B1 is consistent with an observed drop in wind velocities from more than 1000 km s^{-1} down to below 500 km s^{-1}, thus indicating that winds of supergiants later than B1 are not fast enough to initiate shocks strong enough to produce X-ray emission.

Manfred Cuntz: (short presentation) I present some preliminary results regarding the calculation of longitudinal MHD flux tube models for K2 V stars with different levels of magnetic activity. The concept is that magnetically more ac-

tive stars are faster rotators which have 1) more flux tubes and 2) narrower tubes on the stellar surface. Of course, (2) is a consequence of (1) as more tubes have less space to be spread. The shape of the tubes is given by the magnetic filling factor, which is calculated on a $f_0 B_0 - P_{\rm rot}$ relation based on the data given by Rüedi et al. (1997) The models make also use of revised magnetic energy fluxes given by Ulmschneider & Musielak (1997) which are applied at the bottom of the tubes. Our result is that the shape of the tubes controls the channeling of the magnetic wave energy, which determines the shock strengths, the heating rates, and the net radiative cooling. For models with increasing rotation periods, it is found that the net radiative cooling rate in Mg II k at different heights (800 and 1100 km) for *one* tube forms first a plateau and then decreases. However, if this result is scaled by the different numbers of tubes on the stellar surface the decrease of $F_{\rm MgII\,k}$ is magnified by 1–2 orders of magnitude *and* the extension of the plateau is reduced (if they exist at all). Both results are consistent with observations.

Wolfgang Kalkofen: In the case of the chromosphere of the Sun, the periods observed in magnetic flux tubes are near 7 minutes. They therefore point to transverse magneto-acoustic waves (Kalkofen 1997), which appear to be excited episodically. Judging by the power spectrum of chromospheric oscillations in the magnetic network (Lites, Rutten & Kalkofen, 1993), the transverse oscillations have more power than the longitudinal oscillations. For the latter, which are probably excited continually and whose cutoff period is 3 minutes, the mechanism investigated by you, i.e., turbulent excitation, probably provides the correct explanation.

Peter Ulmschneider: I think one must be very careful to argue on basis of some strong observational signal about the importance of certain heating mechanisms. For instance, the 5-min oscillation proved fruitless for the acoustic heating of the chromosphere. The longitudinal MHD tube wave generation is based on the Kolmogorov energy spectrum of turbulent convection and thus has a wide range of high frequencies which cannot be easily observed. The present *monochromatic* wave computation is made only for computational simplicity. An improved computation will use a *wave spectrum*. Longitudinal waves form shocks easily and thus easily heat flux tubes. Transverse Alfvén waves are also produced very efficiently (actually the generated flux for these waves is about 20 times higher). But the problem is to convert the wave energy by mode coupling into longitudinal waves and thus to dissipate the wave energy. It thus appears that the low and middle chromospheric flux tubes are heated primarily by longitudinal MHD waves and that transverse Alfvén waves are responsible for the heating of the high chromosphere and transition region.

4. Polar Spots

4.1. Introductory Talks by A. Hatzes and S. K. Solanki

Are they real? Here are three recent findings why the answer might be yes: Hatzes et al. (1996) ruled out gravity darkening, temperature dependence of line strength, differential rotation, and a bright equatorial band as cause. Unruh & Collier-Cameron (1998) investigated the sodium doublet in AB Dor and

found essentially the same map from conventional Doppler mapping lines and concluded that polar spots are not an artifact of chromospheric emission reversals. And, third, efforts to "tweak" activity to produce polar spots have generally failed (see the poster paper by Bruls, Solanki & Schüssler on "A non-LTE analysis of Doppler-imaging lines").

> *Out damned spot. Out, I say!* — (A "dramatic" Mr. Hatzes at the end of his presentation.)

However, if we believe in their existence, a series of outstanding problems must be addressed: How are they formed? Is it really due to the dominance of the Coriolis force over the buoyancy force as proposed and modelled by Schüssler & Solanki (1992) and Schüssler et al. (1996)? What are the parameters for polar-spot/no-polar-spot stars (rotation rate, convection-zone depth, age, etc.)? Why are spots seen close to the equator where the flux-tube models of Schüssler & Solanki can not place any spots? And finally, how do active latitude bands fit into this spot morphology? Do bands and polar spots represent different dynamo mechanisms?

The current theory is basically a straightforward extension from our knowledge of the Sun to rapidly rotating stars. It explains high-latitude spots on rapid rotators and equatorial spots on slow rotators like the Sun. Obviously, the problem is to find an explanation of the low latitude spots on fast rotators. Here are a few possible explanations:

1. In stars with small radiative cores, i.e., giant stars, "poleward slip" causes free loops to form in the convection zone. Where do these go? To the poles or do they move out to the surface along the equatorial plane?

2. Our current flux-tube model is for single stars. Polar spots are often observed on stars in close binaries. Surfaces of equal angular momentum in the convection zone in close binary components are different than for single stars.

3. What about inverse meridional circulation? Pieces may break off the "polar" spot and coalesce to form largish spots near the equator.

4. Equatorial spots may be formed from fields created by a second dynamo in the convection zone while the polar spot is from fields created by the solar-like boundary layer dynamo.

Clearly, there is plenty of stuff to discuss ...

4.2. Discussion

Ed DeLuca: There are two problems with the polar-slip explanation of flux emergence at the equator: 1) If the flux ring is strong it will collapse fast (see DeLuca, Fisher & Patten 1993) 2) if it does reach the surface then will it form a spot? How does convective collapse work for free loops?

Sami Solanki: Whether the free or O-loops will emerge or collapse first can only be decided by carrying out the necessary simulations. Convective collapse is

indeed quenched in *small* free loops. However, we are dealing here with large free loops, many scale heights across. For these I expect convective collapse to be considerably more efficient.

Steve Saar: Sami's comment on the importance of duplicity on spot patterns is important, but there are still cases of single, rapidly-rotating dwarfs with equatorial or near equatorial spots (LQ Hya, AB Dor, HD 129333) which still lack explanation within the current framework of flux-tube emergence.

Ed DeLuca: It is not difficult generating magnetic fields in convection zones. We can not predict how strong the fields will be, we can not explain why the Sun has fields of a particular amplitude, but there will be field generation in the convection zone.

Nikolai Piskunov: The presence of high-latitude spots on active stars is reliably established. What needs to be studied is how accurately can we map those features. Currently, different spectral lines give different results for polar/high-latitude spots. Only after we start getting consistent results, may we look for correlations between surface gravity, rotation, and the latitude distribution of spots.

Brendan Byrne: I would like to comment on a number of points: 1) we should not be distracted too much by models which invoke duplicity since many single dwarf stars also show polar spots; 2) the large amplitudes of broad-band optical light curves require very substantial low-latitude spot distributions; and 3) template line profiles for Doppler imaging are made either by broadening the spectrum of a quiescent star or using a standard model atmosphere code. The atmospheres of the most active stars may deviate substantially from these templates. Therefore, stationary features on the line profiles should be treated with caution.

Andrew Collier Cameron: The different profiles seen in different lines are very often due to differences in the relative strengths of low and high excitation lines in the spectrum of the spot and the photosphere. Cool spots give much stronger bumps in high-excitation lines than in low-excitation lines because the absorption in the spot spectrum is much weaker.

Klaus Strassmeier: If you properly model the spot's as well as the photosphere's spectrum in the computation of your local line profile, then there should be no differences between low and high-excitation lines. A recent paper on IL Hydrae by Weber & Strassmeier (these proceedings) compares maps from six different line regions and they all look amazingly similar, at least within the current accuracy of Doppler imaging, and all of them show a polar spot.

Andrea Dupree: *EUVE* emission suggests that polar features of high density are formed in all sorts of rapidly-rotating stars as seen from spectroscopic diagnostics in the corona (see proceedings CS9). More direct evidence comes from 44 Boo (Brickhouse & Dupree 1998, and these proceedings) where the feature is not eclipsed and therefore must be at high latitudes.

Brendan Byrne: Spot umbrae are *dark* in high temperature emission lines because the rigid magnetic structure "freezes" the processes which heat the 5–8×10^6 K plasma. Therefore it seems unlikely that this gas is evidence for polar photospheric spots.

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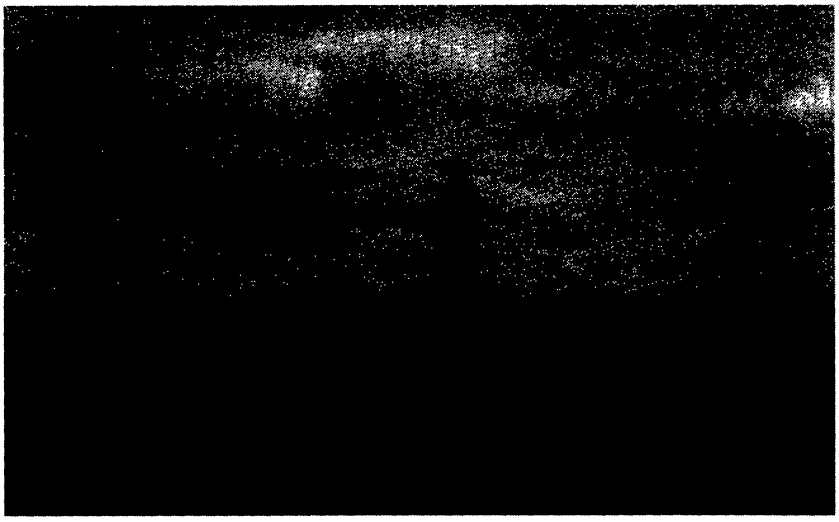
"Last one aboard is all wet...so is the first one."



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CD–273