The A-Star Puzzle
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A stars as physics laboratories

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Abstract. Stars in various parts of the HR diagram often have atmospheres in which the departure from the simplest kind of plane-parallel model is largely dominated by a single physical effect. For example, massive stars and giants exhibit symptoms of strong winds and lower Main Sequence stars are very strongly influenced by the presence of deep and energetic envelope convection. Main Sequence A stars, in contrast, appear to display the competing effects of several physical effects of comparable magnitude. The effects which can be detected by observation include large and relatively simple magnetic fields, strong surface convection, pulsation (often in multiple modes), diffusion of specific species under the competing influences of gravity and radiative acceleration, and (more indirectly) internal turbulent mixing, weak winds, and non-thermal heating. This situation makes these stars extremely useful as laboratories to explore and to understand the physics of these various phenomena, and how these effects interact with each other. This review will summarize some of the interconnections that are gradually being understood and emphasize some of the major remaining problems.

Keywords. Convection, diffusion, turbulence, stars: atmospheres, (stars:) Hertzsprung-Russell diagram, stars: magnetic fields, stars: rotation, stars: winds, outflows

1. What are the A stars?

It is interesting to start our discussion by recalling some general characteristics of A stars. On the Main Sequence, A stars have effective temperatures between about 10000 and 7000 K. Popper (1980) lists a number of A stars in EB systems. They range in mass from 2.6 to 1.6 $M_\odot$. The actual mass range may be somewhat larger. From the models of Schaller *et al.* (1992), stars as massive as 3.5 $M_\odot$ evolve to effective temperatures less than 10000 K before leaving the Main Sequence. If we take the actual mass range of stars that spend some part of their Main Sequence lives as A stars as between about 3 and 1.6 $M_\odot$, the Main Sequence lifetimes range from 6×10^8 to 2×10^9 yr, and the luminosities range from about 40 to 10 $L_\odot$ on the Main Sequence.

It is easily forgotten that the effective temperature of a star evolves significantly during its Main Sequence lifetime, decreasing by about 30% from the ZAMS to the TAMS. Thus a star with a mass of a little more than 3 $M_\odot$ will be an A star only near the end of its Main Sequence life, while a star of 1.6 or 1.7 $M_\odot$ will become an F star during the Main Sequence stage.

Main Sequence A stars cover the transition region in the HR diagram between stars with Sun-like evolution to the giant branch with a strong increase in luminosity up to about 10^3 $L_\odot$ at the helium flash, and stars massive enough for evolution to the helium flash to occur at roughly constant luminosity, as is the case already around 4 or 5 $M_\odot$ (e.g., Schaller *et al.* 1992).

The surface convection zone (H I – H II, He I – He II and He II – He III) extends to a depth where the temperature is of order 50000 to 150000 K, and involves about 10^{-8} or more of the stellar mass.

For many of the problems that interest us, it is important to consider the progenitors of the A stars, the Herbig Ae stars. These stars have similar masses to the Main Sequence A stars, and also similar effective temperatures, but are often several times more luminous than the Main Sequence stars of the same $T_{\rm eff}$. They are typically located in the galaxy in regions of recent star formation, along with the lower mass T Tauri stars. With increasingly powerful telescopes and the ability to observe in new wavelength regimes such as X-rays, we are now rapidly accumulating valuable information about these stars, and developing reasonably comprehensive (but still mostly one-dimensional) models both of the underlying star and its active chromosphere, disk and wind (e.g., Catala 2003).

A giants and supergiants, of course, originate as more massive stars, above 4 or 5 $M_\odot$. For such stars the A star phase may be reached as the star evolves rapidly to the red giant state after reaching the Schönberg-Chandrasekhar limit. In this case, the star is an A star for only $10^5 - 10^6$ yr.

2. What characteristics make A stars useful as physics laboratories?

An extremely interesting process in its own right, and a powerful probe of other physical processes in the stellar interior, is the microscopic diffusion of trace elements under the combined influence of gravity and radiative acceleration. This process can be a very valuable probe of other physical processes if competing processes do not occur with much higher velocities.

The characteristic time scale of this process is easily estimated. If we take the typical speed of a trace ion to be the thermal speed $v_{\rm th} \sim (2k_{\rm B}T/Am_{\rm u})^{1/2}$, the collision time is of order $t_{\rm coll} \sim 1/(n_A v_{\rm th}\sigma)$. If we assume that the trace ion is accelerated between collisions relative to the dominant H medium by gravity and radiation with some net acceleration $g_{\rm e}$ (typically of order 10^4 cm s^{-2} in Main Sequence A stars), an estimate of the diffusion velocity is $v_{\rm dif} \sim g_{\rm e} t_{\rm coll}/2$. Near $\tau = 1$, the number density of scatterers is of order 10^{14} cm^{-3}, and the diffusion speed is a small fraction of 1 cm s^{-1}.

In contrast, in O and early B stars, winds can occur with mass loss rates as large as 10^{-8} $M_\odot$ yr^{-1}. If this is assumed uniform over the star, an estimate of the vertical velocity of the wind is given by $\dot{M} \approx 4\pi R^2 n_A v_{\rm wind}$. A mass loss rate of 10^{-8} $M_\odot$ yr^{-1} corresponds to velocity of some m s^{-1}. This velocity is much larger than the typical diffusion velocities, and as a result, large surface abundance variations are not able to develop. Thus chemical anomalies are generally ineffective as tracers of internal physical processes in hot stars.

A different situation occurs in the cool stars (mid F and later), where a deep convection zone is present. Again the velocities (which can rise to a significant fraction of the speed of sound, thus up to a couple of km s^{-1} even in the atmosphere) are far larger than the diffusion velocities, so the convective region is extremely well-mixed. Diffusion can occur into and out of this region at the bottom, but because the mixed reservoir is massive, at most rather small changes in the surface abundances occur. Again, abundance anomalies are not very useful as tracers of interior processes.

In contrast, the envelope convection in A and late B Main Sequence stars occurs only in a very shallow layer of tiny mass, and winds (if any) are apparently quite weak. Thus no large competing velocity fields prevent the development of abundance anomalies at the stellar surface. These can serve as valuable tracers of processes that modify or compete with diffusion in the stellar interior. This is perhaps the fundamental reason that middle Main Sequence stars ("tepid stars") are particularly useful as stellar physics laboratories.

A further important advantage of A stars, in contrast to more massive Main Sequence stars, is that we are able to observe the later stages of the pre-Main Sequence phase

(Herbig Ae stars). We may hope that in the near future we will be able to trace some of the interesting phenomena discussed below from this early evolutionary stage.

Finally, there is also an important observational characteristic of A stars that offers significant practical advantages. These stars are hot enough not to have molecules in their spectra, making spectral analysis enormously simpler than for G, K and M stars, but they are cool enough to have relatively rich line spectra in the easily accessible visible spectral window. This characteristic is not fundamental, but it certainly is valuable as we consider using A stars as laboratories to study stellar physics.

3. Chemical peculiarities: diffusion as a physical process

For later discussion, it is useful to recall the basic characteristics of trace element diffusion (Michaud *et al.* 1976). (1) Under the action of gravity alone, all ions heavier than H would slowly settle towards the interior of the star. (2) The outward flow of radiation in the star exerts an acceleration on atoms and ions. This acceleration is largest for ions of locally low abundance, and for ions with a rich array of low-lying energy levels. The acceleration *per ion* diminishes with increasing abundance and for ions in noble gas states. (3) The *net* acceleration at one level on a particular ion may be upwards or downwards. This acceleration will vary with depth and will *evolve in time* as ions diffuse from one level to another. (4) Consequences of internal diffusion are visible at the surfaces of many A stars, and may even include pronounced vertical stratification within the atmosphere. (5) Diffusion is modified by competing velocity fields inside the star and consequences of this competition may become visible at the surface (e.g., Richer *et al.* 2000). (6) The upper boundary conditions (presence and nature of a stellar wind, possible accretion) also modify atmospheric abundances (Vauclair 1975, Babel 1992). (7) Observationally we see that diffusion near the surface is profoundly modified by the presence of a strong magnetic field. A magnetic field strongly inhibits horizontal mixing and thus makes possible horizontal variations in composition. High in the atmosphere (but not elsewhere) ions are forced to drift along field lines. However, the basic mechanism leading to large surface inhomogeneities remains mysterious (Babel 1992). (8) Note that trace ions may diffuse upwards or downwards through a convective region. They will be homogeneously mixed in the convective zone, but may be added to or removed from such layers at their boundaries.

4. Chemical peculiarities: diffusion as a probe

Up to now it has proven remarkably difficult to get the results of diffusion computations to resemble closely the surface abundance patterns observed in various types of tepid stars. It seems likely that this is due to that diffusion competes with mixing processes in the stellar interior, and may be strongly influenced by the (very uncertain) upper boundary conditions at the top of the atmosphere. This sensitivity to competing processes makes diffusion, as observed in the atmospheric chemistry of various stars, potentially a very important probe of such invisible processes.

A very interesting aspect of the A stars is that one very important competing process, envelope convection, varies dramatically from the most massive to least massive A stars in the depth of the layer to which it operates. Thus in a limited mass range we have, in principle, the possibility of using the lower boundary of the convective zone as a kind of movable probe of the effects of diffusion at various depths.

A very important recent development, for testing the time dependence expected for the results of diffusion against observed abundance patterns in stars of know ages, has been the great improvement in astrometric data (from the Hipparcos, Tycho, and Tycho-2 data) for cluster stars, whose ages may be determined much more securely than the ages of most field stars. These data have greatly clarified which stars found in the fields of clusters and associations are actually physical members of these groups, and thus have relatively well-defined initial chemical composition and ages. Cluster stars are being exploited by Hui-Bon-Hoa & Alecian (1998) to study the evolution of anomalous abundances, and thus the effects of diffusion, in Am stars, and by Bagnulo and collaborators (still unpublished) to study the evolution of magnetic fields through the Main Sequence phase.

A very nice example of using diffusion to probe other physical effects is Sylvie Vauclair's (1975) hypothesis for the origin of He-strong magnetic B stars. These are stars having $T_{\rm eff}$ around 20000 K in which He is greatly overabundant in the atmosphere, in contrast to all cooler magnetic stars in which He is underabundant, almost certainly due to the downward diffusion of this element, which has little support from radiation. The occurrence of He-strong stars appears to be due to the presence of a weak stellar wind of order of $10^{-12}\,M_\odot$ yr^{-1}. This wind exerts a strong frictional drag on the ionized He below the atmosphere, lifting it into the atmosphere. At this level, the He ions become neutral, greatly reducing their interaction with the wind, so above this level the He atoms are *not* dragged along with the wind, but collect in the atmosphere. The beauty of this hypothesis is that it reveals the presence of an otherwise (currently) undetectable wind.

If winds of similar mass loss rate occurred in late B magnetic stars, they would be expected to lead to overabundances of Ne and/or O at the surface (Landstreet *et al.* 1998). Since these are not observed, either the winds do not occur with the necessary minimum mass loss rate, or they are not turbulent enough to be well-mixed. (Note that in any case winds much stronger than 10^{-12} $M_\odot$ yr^{-1} would erase most atmospheric chemical anomalies as they do in hot stars, so the occurrence of such winds seems to be excluded.)

Another nice example of using diffusion to probe invisible processes is offered by Richer *et al.* (2000) who have carried out computations of the expected abundance anomalies in Am stars. They find that if diffusion is allowed to occur in their models without competition, the surface anomalies are considerably larger than are observed in actual Am stars. Much better agreement with observation is obtained by assuming that meridional circulation currents are turbulent, and are able to mix somewhat (though not to completely homogenize) the outer layers down to a level including about 10^{-4} $M_\odot$. Again we have an example of using surface abundances to explore otherwise invisible internal mixing processes.

As a final example, Charbonneau & Michaud (1988) have proposed that the occurrence of the HgMn peculiarities in late B stars is limited to stars with equatorial rotation velocities of less than about 75 km s^{-1} because of rapidly increasing competition with mixing due to meridional circulation currents. Diffusion thus appears to probe meridional circulation.

5. Atmospheric velocity fields

The widely used mixing length model of convection is really only an order-of-magnitude estimate of the effects of convection. In situations in which convection operates "efficiently", - in which the density and the velocity of the convecting gas are high enough to transport almost all the outward flux of energy and the temperature gradient is forced to the local adiabatic gradient, mixing length theory provides an adequate framework for computing stellar structure. However, in low density regions such as the outer envelopes of stars, convection is inefficient, and one is obliged to compute the flux carried by both convection and radiation. In this situation the inaccuracy of the mixing length model is an important limitation on the accuracy of stellar models.

In principle this situation can be improved by numerical computation of the structure of a convecting layer from physical first principles. However, such computations are limited in scope by the enormous memory requirements, by the long thermal relaxation times of inefficiently convecting gas, and by the necessity to model sub-grid scale dissipation. For the near future, such computations will not provide a solution to the need for a better model of convection, but very interesting results have been presented at this meeting by Freytag (2005) and by Trampedach (2005).

Several improved models of convection which are computationally tractable have been developed in recent years (Canuto & Mazzitelli 1992, Kupka & Montgomery 2002), and are beginning to be applied to the computation of the structure of inefficient convective regions. Testing the predictions of these models is an important part of this process. A stars are potentially an important laboratory for such tests, since in such stars an inefficient convection zone reaches into the atmosphere, where in sufficiently slowly rotating stars its velocity field is directly observable in deviations of line profiles from those predicted by simple models such as isotropic microturbulence (Landstreet 1998).

One intriguing result is already available from such studies, which have been carried out for some years for lower Main Sequence stars. In cool stars, the profiles of spectral lines are observed to have an extended long-wavelength wing, which is interpreted as a symptom of a convective pattern of slowly rising flow over a large fraction of the surface, together with a rapidly descending return flow over a smaller surface fraction (e.g., Gray 1989, Dravins 1990). Such a flow pattern is consistent with the results of numerical simulations, and detailed observations of the solar surface. In A stars, the extended wing is on the *short* wavelength side of the spectral line, suggesting that the convective structure is quite different from that of cooler stars, possibly with rapid updrafts on a small fraction of the surface and slower downdrafts over much of the rest, as is the case in the Earth's atmosphere. Furthermore, the velocities inferred from the study of A stars suggests that the speed of convective flows in the atmospheres of such stars are significantly larger than in the cool star case. The results for A stars are presently in serious disagreement with the numerical hydrodynamical computations of Freytag (2005) and Trampedach (2005), both of whom find that A star convection is structurally similar to that of the Sun.

6. Magnetic fields

Another observable physical effect in many A and B stars is the presence of a global magnetic field of considerable strength. This meeting has been dedicated to the memory of the discoverer of these fields, Horace Babcock, and of Vera Lvovna Khokhlova, a great pioneer in modelling the surfaces of magnetic stars. But on a much happier note, we have been very fortunate to have the second great pioneer of magnetic field observations, George Preston, here to participate in the meeting with us.

The magnetic fields of A and B stars dramatically affect the stars in which they occur, both in the nature of their atmospheres and in global properties. In the atmospheres, the magnetic stars have highly distinctive abundance anomalies which vary systematically with effective temperature, but also considerably from star to star among apparently rather similar stars. Furthermore, some of the stars have substantial abundance variations over the surface, and there is strong evidence for vertical stratification (both in magnetic and non-magnetic stars) (see reviews by Mathys (2005) and by Ryabchikova (2005)).

Two extremely interesting global effects of these fields occur as well. One important effect is that most (but not all) magnetic Ap stars have only about 0.1 of the angular momentum per unit mass found in normal A stars, while a few have less than 10^{-4} of the normal specific angular momentum. Since only a very small fraction of magnetic Ap stars are in close binary systems, this must be due to the magnetic field (see Mathys 2003). The other effect is that some of the coolest magnetic Ap stars pulsate, usually in a number of non-radial modes, with periods in the range of 4 to 15 min (see the review by Kurtz *et al.* 2005).

These stars provide us with a really valuable laboratory to observe the interactions of a strong magnetic field with a large-scale plasma, which in the cooler Ap stars is probably unstable to convection according to the Schwarzschild criterion. These tepid magnetic stars have two great advantages over the cooler magnetic stars as laboratories. First, that a range of field strengths, strong enough to be easily observable, are available in the numerous magnetic Ap stars. And second that the field is relatively homogeneous over the whole surface, making it far easier to study than that of unresolved magnetically active cool stars whose spectra are largely dominated by the hotter, unmagnetized plasma.

The list of unsolved problems concerning such stars is impressively long. (1) It is still uncertain how these stars lose so much angular momentum, although Stępień (2000) has proposed a very plausible semi-empirical theory involving magnetic coupling during the pre-Main Sequence phase to an accretion disk and to a wind. (2) Moss (2001) has carried out a number of illuminating model calculations of fossil field evolution during the Main Sequence phase, but it is not yet possible to link these closely to the observed fields, or to test the results observationally. In fact, it is still not completely clear that these fields are really fossils, although this is the general view. (3) On the basis of similar birth rates and the correct relative field strengths, it appears that the fields in Main Sequence Ap stars may be the progenitors of megagauss fields in magnetic white dwarfs (Angel *et al.* 1981). However, no calculations are available to really support this idea. (4) Detailed computations of atomic diffusion (e.g., Babel & Michaud 1991) have not yet succeeded in reproducing the observed abundance patterns in any magnetic Ap, and have been even less successful in explaining the origin of the abundance patches. One of the main uncertainties here is whether a stellar wind is present, and if so whether it is well-mixed or separated (i.e., consists mainly of ions driven out by radiation, without dragging along unsupported ions such as H and He). A wind could greatly modify the elements expected to accumulate in the atmosphere. Babel (1992) has suggested that magnetic control of a wind could account for the occurrence of abundance patches. (5) Finally, it seems very likely that the structure of the atmosphere of a magnetic Ap star, in which the magnetic field leads to significant forces and the abundances are probably quite non-uniform vertically, is very poorly described by the atmosphere models currently used to model observed spectra. The consequences of this uncertainty are still unexplored (see e.g., Kochukhov *et al.* 2002).

Although magnetic A stars are potentially an extremely valuable laboratory for stellar magnetohydrodynamics, much work still needs to be done in the lab before it will be fully functional.

7. Rotation and braking

Rotation of peculiar A stars has recently been reviewed by Mathys (2003, see also other contributions in this volume). The evolution of angular momentum under various circumstances is another area where A stars (together with the Herbig Ae stars) can provide an important laboratory. One of the great values of this particular laboratory is that a wide range of parameters is found. Among the A stars we have examples of stars which have some of the highest stellar values of specific angular momenta (of order

3×10^{17} cm^2 s^{-1}, corresponding to $v \approx 300$ km s^{-1}or $P \approx 0.5$ d), and some of the very lowest (a few magnetic Ap stars have rotation periods of decades or more). The observed values of specific angular momenta cover at a range of almost 10^5 from highest to lowest.

On one hand, this means that we can readily explore the effects *of* rotation, for example in producing mixing through meridional circulation that may compete with diffusion. Among the nonmagnetic A stars a wide range of periods is available. It has been argued (Charbonneau & Michaud 1988) that the restriction of the HgMn peculiarity to stars with $v \sin i < 75$ km s^{-1} is a consequence of the rapidly increased efficiency of mixing above this rotation rate.

On the other hand, it is also possible to use the A stars to look at the effects of other physical mechanisms *on* rotation and its evolution. It appears (North 1998) that the magnetic stars have been slowed during the pre-Main Sequence phase. Stępień (2000) has explained how magnetic interaction with a disk and wind could achieve this. Stępień & Landstreet (2002) have discussed how the same physics might be extended to explain how the longest periods might be produced, and why most of the shorter-period magnetic Ap stars have a large angle between the axis of their roughly dipolar structure and the rotation axis, while in long-period magnetic Aps stars this angle is usually small (Landstreet & Mathys 2000).

Similarly, a large fraction of HgMn and Am stars are in close binary systems, some of which do not show stellar rotation synchronized with the orbital period. These systems should furnish valuable information about angular momentum exchange in close binaries.

One very intriguing recent result is observational evidence that the rotation periods of some magnetic Ap stars are note precisely constant for a period of several decades (see Pyper and Adelman 2005). The interpretation of this phenomenon is still quite uncertain.

8. Pulsation

Among the A stars, three different kinds of pulsation are recognized. The pulsation properties of the pulsating A stars are potentially extremely important in the context of using such stars as laboratories. As pulsation modes are identified and compared to models of these stars, the pulsations will furnish enormously valuable constraints on the internal structure of various types of A stars.

The best known pulsation mode among the A stars is the δ Scuti type of pulsation. δ Sct variables are late A Main Sequence stars. Some pre-Main Sequence Herbig Ae stars are also δ Sct variables. These stars pulsate with periods of the order of 1 or 2 hours, and show both light and line profile variations. In these stars up to roughly 30 periods are observed by long multi-site ground-based observing campaigns (e.g., Breger *et al.* 2002). The observed pulsations are primarily low degree l, low overtone n p-modes (that is, the restoring force is primarily due to gas pressure, so that the oscillations resemble sound waves). This type of pulsation is, roughly, an extension of the classical Cepheid Instability Strip to the Main Sequence (Unno *et al.* 1989).

Some of the coolest magnetic Ap stars also exhibit short-period (4 to 15 min) light variations, typically with several frequencies that may come and go. Such stars are known as roAp (rapidly oscillating Ap) stars. Recently line profile variations, usually with one of the photometric periods, have also been detected in some of these stars, although often only in a few lines, particularly those of doubly ionized rare earths. A rich array of phenomena connect the pulsations to the magnetic fields. For example, the pulsations seem to be at least approximately aligned with the axis of the roughly dipolar field. These pulsations are low-l, high-n p-modes. The driving mechanism for the pulsations has not yet been securely identified (e.g., Shibahashi 2003).

A recent addition to the classes of pulsating A stars is the γ Doradus stars (Kaye *et al.* 1999, Mathias *et al.* 2004). These are multi-periodic variables showing variations with periods of the order of 0.4 to 3 days. Variations are seen in both light and spectral lines profiles. The γ Dor variables range roughly from A7 to F5 and are close to the Main Sequence. In this case, the occurrence of multiple long periods clearly points to non-radial g-mode pulsations (that is, the restoring force is mainly due to buoyancy forces rather than to gas pressure).

Because these classes of pulsators all are known to show multiple periods of variation, the number of constraints on internal structure available in principle is interestingly large (although we will not have anything like the astonishingly detailed information emerging about the interior of the Sun from helioseismology any time in the foreseeable future). However, to date it has proven very difficult to identify the observed frequencies with model pulsation frequencies (particularly for the δ Sct stars), so this potential is still largely unrealized.

What is needed observationally is a still larger number of observed frequencies. Such data are obtained from the ground only by organizing large multi-site photometric or spectroscopic campaigns involving several observatories and observing runs lasting days or weeks. Campaigns of this sort have produced some really remarkable data. For a few objects, the situation is shortly going to become remarkably better due to observations from photometric satellites such as MOST (launched and working), COROT and MONS (both to be launched in the near future), from which it should be possible to detect substantially weaker pulsation modes (a few *micro*magnitudes) with greatly improved frequency resolution and freedom from aliases.

Theoretically, the pulsation models depend on a large number of parameters, mass, age, metallicity, rotation, magnetic field, and very large model grids, together with algorithms for searching such grids for pulsation frequency sets approaching observed sets, will be needed. Indeed, for the roAp stars the situation is even worse, as one does not yet understand the mechanism that aligns the pulsations near the magnetic axis, or the mechanism that selects only certain modes to pulsate with observable amplitudes, or why some cool magnetic Ap stars pulsate and others do not.

Our understanding of the pulsating A stars is presently frustratingly limited, but this is a field in which rapid observational and theoretical progress is occurring. It is a field which offers really important rewards as models account for more and more of what is observed. We can look forward to having an increasingly detailed view of the interior of some of the A stars, which will make it possible in turn to study effects of invisible physics. In the future asteroseismology may make it possible to constrain the size of the internal magnetic field, to study the internal distribution of angular velocity, and to constrain the spatial variation of chemical abundances. These are such important potential rewards that we may be almost sure that progress in this field will continue at a rapid pace (see Christensen-Dalsgaard 2003).

9. Conclusion

It is clear that the A-type stars that are the subject of this meeting offer a really wide range of possibilities for use as laboratories to study stellar physics.

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Discussion

FREYTAG: What steps do you recommend to extract the information buried in the complex line profiles you showed [profiles of the very sharp-lined Am star HD 108642, from Landstreet (1998, *A&A*, 338, 1041)]?

LANDSTREET: I have personally been trying to model these data using simple parameterized velocity fields, for example specifying vertical upward and downward flows over specified fractions of each integration grid area in my spectrum synthesis code. When I do this, I find that I can get line profiles that resemble those of strong lines in HD 108642 by assuming that the microturbulent velocity increases with height in the atmosphere, along with global vertical flows of the order of 8 $\mathrm{km\,s^{-1}}$upward over 20% of the area, and downward at 2 $\mathrm{km\,s^{-1}}$over the remaining area. Thus it appears to me that the data are suggesting a flow pattern which is opposite to that of the Sun, with rapid downdrafts in smaller regions and slow updrafts over large areas. But these results are still quite preliminary.

BALONA: In the pre-Main Sequence phase, a magnetic field inclined to the rotational axis by an angle β will experience a torque by coupling to the circumstellar disk, which will tend to further increase the angle of inclination of the magnetic axis, β. One may, therefore, expect to find a relationship between β and the time spent in the pre-Main Sequence phase, i.e., between β and mass. Is this confirmed by observations?

LANDSTREET: The higher-mass magnetic Bp stars spend of order 10^7 yr as PMS stars. They seem to never be able to slow to rotation periods longer than a couple of weeks, and generally seem to have a large angle between their magnetic and rotation axes. In contrast, the cool magnetic Ap stars, which spend more like 10^8 yr as PMS objects, sometimes exhibit very long rotation periods, of order years or more, and these very slow rotators seem to usually have their field and rotation axes parallel to each other. Perhaps this is the relationship that you are suggesting.

RYABCHIKOVA: Could you comment on the possibility that an A stars may lose a substantial part of its angular momentum while on the Main Sequence?

LANDSTREET: North (1984, *A&A*, 141, 328) showed from cluster data that Ap Si stars do not appear to lose angular momentum while on the Main Sequence. For cooler magnetic Ap stars, which are (mysteriously) largely absent from clusters, the only strong argument I know of that little or no angular momentum is lost on the Main Sequence is the absence of evidence for circumstellar material that could carry off that angular momentum.

RYABCHIKOVA: If we observe a weakly magnetic peculiar star near or beyond the TAMS, and this star has a very small rotational velocity, does this mean that the star arrived on the Main Sequence with slow rotation?

LANDSTREET: From my comment immediately above, I would be inclined to think that most or all of the angular momentum loss for a magnetic star occurs during the PMS phase. However, for an individual star, one cannot rule out the possibility of interaction during the star's life with an interstellar cloud which could be given some of the angular momentum.