THE MAGNETIC FIELDS IN THE STELLAR PHOTOSPHERES

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The theory of stellar atmosphere is, we may say in a sense, an applied solar physics. This is a great advantage for the part of stellar astronomers because, once solar physicists have a good theory on a solar phenomenon, stellar astronomers can apply it to stars with various values of gravity and effective temperature. However, it does not mean that this method always works well. Sometimes the theory turns out false after it is applied to stars as in the case of coronal heating by sonic waves. And sometimes a good theory for the solar phenomenon does not exist because solar physicists are content with semi-empirical models. In such a case, stellar astronomers are at a loss what to do or how to think because they have neither enough observational material to build a semi-empirical model nor a guiding principle for a theoretical study. A good example is the study of the region with strong magnetic field near the surface, i.e. sun-spots. Several theoretical attempts have been made of course, but they were unsuccessful. They do not provide any explanations concerning the fundamental characteristics of the sunspots such as, why the boundaries of the umbras and penumbras are sharp, why the spots are dark, what causes the Evershed flow, etc.

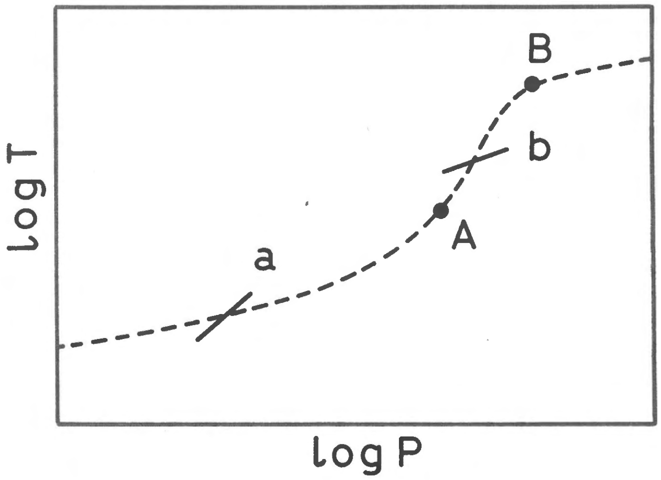
Many Ap stars are known to have strong magnetic field, the strongest average surface field observed being 34 kilo-gauss (Babcock 1958, 1960). These strong surface fields are believed to be related to some gigantic stellar spots. But, lacking the physical understanding of sun-spots, stellar astronomers cannot predict the behavior of these stellar spots. Therefore, their analysis is sometimes very primitive, and sometimes their research go further and further without checking the reliability of the first analysis on which their works are based. Let us see two important examples.

The gravity and the effective temperatures of Ap stars are comparable to those of late B-type main sequence stars. For the latter stars, log P is 3.1 at the reversing layer (Allen 1974). If we put the value equal to $\log(H^2/8\pi)$, we have approximately H=200 gauss. Therefore, at the surface of magnetic stars, the energy density of magnetic field is larger than the energy density of plasma by several orders of magnitude. It is clear that the atmospheric structure of magnetic stars is not determined without knowing the configuration of magnetic field. Yet, people analyse the spectrum of Ap stars with static plane-parallel models probably because they have sophisticated computer program for computing such models, and also because you solar physicists did not give them a recipe for making theoretical model of the region with strong magnetic field, the sun-spot.

Since Babcock (1958), it has been customary to use an equivalent dipole in order to represent the displacements of Zeeman lines in the two spectra corresponding to two circular polarization. Naturally, it should be considered as a convenient method of representing the average field strength in a simplified manner, and by no means, it should not be taken for granted that the stellar field is really dipole. However, many works have been done with the assumption of dipole field, and sometimes, with more sophisticated "de-centered dipole" or "quadrupole." In this example again, the dipole field or other force-free field was used because it was manageable. In other words, mathematical simplicity was more important than proper representation of physics of the system in their works. Of course, we do not have any guiding principle for the theoretical determination of the configuration of magnetic fields near the photosphere yet. But are we allowed to abandon the physics for that reason? I believe that the first thing we should do for the understanding of stellar spots is to know what physical processes are going on there. Then, we are able to describe the system. If we prefer mathematical or methodical simplicity, then we may have results in numerical form, but we are far from the true understanding of stellar spots.

As one of the trials to attack the problem, I showed in the IAU Symposium No. 93 which was held in July this year at Kyoto (Nariai 1980) that a static solution does not exist for the complex system of plasma, magnetic field, and radiation in the gravitational field.

Today I wish to talk about the behavior of a quasi-stationary magnetic tube filled with plasma moving along the tube. I assume that the atmosphere outside the tube is in quasi-static equilibrium. It is clear that plasma is closer to isentropic in the magnetic tube than in the ambient atmosphere because of the flow in the tube. Then, the stable position of a tube element for which the gravity and the buoyency cancel depends on the entropy gradient in the ambient atmosphere. We do not take the Lorentz force into account for the sake of simplicity. In a radiative atmosphere where $ds/dh>0$, a tube element is in stable equilibrium when it is horizontal. In a super-adiabatic environment ($ds/dh<0$), plasma in a magnetic tube is unstable against up and down motion. With regard to the slope, vertical position gives the stable state. In adiabatic zone ($ds/dh=0$), it is neutral against any change in its slope or height. These conclusions hold without regard to the direction of the flow. For a tube element in the



A schematic log P - log T diagram. A solar type atmosphere without magnetic field (dotted line) is divided into three parts, i.e. radiative zone (left of A), super-adiabatic zone (A to B), and adiabatic zone (right of B). Bold lines a and b correspond to adiabatic vertical tube elements in the radiative- and the super-adiabatic regions, respectively. Scale for log T is twice the scale for log P.

existing structure which does not conform with our results, we may think either that the treatment of the tube and the ambient atmosphere is not good, or that the radiative process is rapid (or the motion of plasma is slow).

As the integration of ds/dx over the distance along the tube gives the inequalities between the entropy inside and outside of the tube, we can use our results not only to the tube and the ambient atmosphere, but also to a larger structure like sun-spots with appropriate corresponding assumptions. We may say that the penumbra or the region of Evershed flow is horizontal because the normal atmosphere at the same height is in radiative equilibrium, and that the wall of the umbra where it is supposed the Evershed flow comes from is vertical because the normal atmosphere at the same height is super-adiabatic. May we also conclude that the stellar photospheric magnetic field is almost horizontal as in the sun-spot penumbra because the atmosphere of B-type stars is radiative.

The direction of the flow determines its thermal character. If the ambient atmosphere is radiative, upward flow (or outward flow in the penumbra) is endothermic and the downward (or inward) flow is exothermic. The situation is opposite in a super-adiabatic region. This may be considered as a modification of adiabatic cooling by Russel (1921) applied to the flow in a magnetic tube. Departure from the ambient atmosphere depends on the heating time scale and the velocity of the plasma. It is easy to understand that the outward flow is below the inward flow for the penumbral region because originally the inward flow has higher entropy than the outward flow.

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