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Raphael Steinitz
Physics, retired
Ben Gurion University
Israel

Athens Institute for Education and Research
8 Valaoritou Street, Kolonaki, 10671 Athens, Greece
Tel: + 30 210 3634210 Fax: + 30 210 3634209
Email: info@atiner.gr URL: www.atiner.gr
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Abstract

Ampere's law, when operative in certain types of Stellar Atmospheres, can generate large-scale Magnetic Fields. We examine the necessary conditions for this to happen, and show that predicted properties of such fields on O, B and A type stars do fit the empirical data. The theory, in its current form, is not applicable to stars with convective envelopes. The ongoing controversy about the origin of these fields, Dynamo or Fossil, can thus be resolved: Surprisingly, both are relevant!

Keywords:

Introduction

We explore the possibility of resolving a long-standing puzzle. In essence, the problem is the origin of *oblique rotator magnetic fields on early type stars*, i.e. on O, B and A stars (a few early F stars may also fall into this category).

In 1897 A. C. Maury discovered some early type (Ap and Bp) stars with "peculiar" spectra. For normal stars on the main sequence, there is a one to one correspondence between their color (i.e. temperature) and their line spectrum. This does not hold for those peculiar stars, exhibiting for example strong lines of Hg or Mn. At that early stage, it was not yet known that these stars carry strong magnetic fields at their surface, nor the close connection between these fields and their spectral peculiarities. In 1947 H. W. Babcock (1947) discovered for the first time a star (not the sun!) with a magnetic field at its surface (78 Vir [HD 11022]). Subsequently, Babcock (1958) prepared a catalog of known (at that time) magnetic stars classifying these stars according to their temporal observed magnetic changes: Stars with periodically reversing fields; reversing fields but non periodic; not reversing field as well as not periodic. Eventually it became clear that they are, in fact, periodic.

As it became known that some stellar atmospheres harbor strong magnetic fields, the enigma we deal with, came into being: *What is the origin of those magnetic fields on O, B and A stars?*

Choice of Sample, Properties and Models

To clarify why we restrict our discussion to the early type stars, we note that stellar emitted radiation is brought to the surface (the stellar atmosphere) of main sequence stars via two different modes: Convection, in later (less massive) type stars (such as our sun), and by radiation in early type stars (the O, B and A stars, and perhaps some early F type stars). Models to generate magnetization in late type stars involve dynamo mechanisms, driven by interaction of convection and rotation of stars. On the other hand, the origin of magnetic fields on early type stars is *not yet clearly understood*.

To proceed, we mention some of the important observed properties of magnetic stars, and subsequently discuss difficulties with models proposed to account for the observations.

Magnetic field periods are in the range of half a day to very long periods;

Each magnetic star has an *individual magnetic curve*. Amplitudes range from within a few Gauss up to 34 KG;

Some stars show polarity reversal, but not all;

Only a small fraction of the O, B and A stars (5% 10%) are known to be magnetic stars;

The fields appear to be *stable* (at least for the time since discovered).

Oblique Rotators

Several models have been suggested to account for the observed periodic magnetic curves. Oscillations of a star were considered, but it was argued that the large size of the star implies periods of some millions of years; on the other hand, horizontal surface oscillations could provide correct periods, but polarity reversal will not be attained. Stibbs (1950), Schwarzschild (1950) and Deutsch (1954) suggested that the magnetic dipole is inclined to the star's spin axis, and that axis is again inclined to our line of sight. We have to consider *two different angles* – inclination (line of sight to rotation axis) and *"obliquity"* angle (Magnetic Dipole to spin axis). With such a model one can account for practically all observed magnetic curves; the *"Oblique Rotator"* model is now generally accepted, consistent with the observations. If inclination and obliquity are both non-vanishing angles, rotation of the star will bring different aspects of the (~ Dipole) to our line of sight. Two important factors are extremely relevant:

Geometry – there is a pronounced *preference* of obliquity angles to be *large* – close to 90 degrees; This is well documented for example in the thesis of Jennifer Power ( ). See Table 1.

Physics – now we come to the *heart of the problem:*

If a star would not rotate, you should expect it to be *spherically symmetric.*

If the star does rotate, the least you should find is *cylindrical symmetry*. Granted, our sun is not perfect in that sense, having spots and other surface magnetic structures, but these are not permanent or lasting the 11- year solar cycle. The presence of a magnetic field *oblique to the spin axis* of the star breaks down

(a) *cylindrical symmetry* of the star, as well as

(b) *reflection symmetry* about the equatorial plane of the star.

Current Models: Dynamo and Fossil Magnetic Field

What are current theories to account for these fields? Two basic ideas prevail: (1) Dynamo –rotation and self –induction create electric currents, so magnetic fields are generated; and (2) Fossil fields – the magnetic fields are remnants of interstellar magnetic fields, frozen into the gas while contracting to form the star. In addition to the basic models, a variety of modifications of the basic principles were suggested. Detailed discussions of the pros and cons of dynamo and fossil theories are given in Mestel (2003). A striking illustration of difficulties encountered with both models is given by HD 72106 (Folsom, 2007), a *binary system*:

HD 72106

	mass	radius	temperature	*inclination*	*obliquity*
star A	2.4	1.3	11000	23	60
star B	1.8	1.4	8500	---	---

(Mass and Radius are in Solar units; Temperature - in Kelvins; Inclination and Obliquity – in Degrees). The two (binary) stars are not identical, but pretty similar. The obvious difference is that star A is an Oblique Rotator while the second star is normal. If the Fossil theory holds, why would only one star retain the field, although both originate from the same interstellar cloud? On the other hand, if there is an internal Dynamo mechanism, it operates only in one and not in both stars?

Most important Attributes

We now recall the most relevant attributes of the known magnetic stars: (1) *Symmetry is lost*, as displayed by non vanishing obliquity, being *preferentially large*; (2) Fields are stable, at least for the length of time recognized as magnetic ones; (3) Only a *small fraction* (5% - 10%) of O, B and A stars are magnetic; (4) *Individuality*: different field amplitude, different age, different obliquity and different (space) location.

These attributes convince us that the origin of the magnetic fields is *not* connected to any intrinsic property or mechanism *operating within the star*. Instead, we conclude that an *external agent acting at random* is responsible for the creation of magnetic fields in the O, B and A stars. To discover that agent, we now examine the process of magnetic field generation. An *electric current*, I, *is needed* to induce a magnetic field B (Ampere's law).

The Electric Field

Let us consider now a barometric stellar atmosphere composed of fully ionized

plasma. Pannekoek (1922) and Rosseland (1024) argued as follows:

The scale height of a barometric atmosphere is H:=(kT/mg); if ions and electrons would not have electric charge on them, $H_i << H_e$ since $m_e << M_i$; in reality they are charged. Since electric interaction between them is very strong, for a plasma atmosphere $n_i \approx n_e$, and also $H_i \approx H_e$. For this to hold, an electric field E must be present. To find its value, we compare the hydrostatic equations of electrons and protons:

$$(I) \quad \nabla p_i = n_i(-M_i g + eE)$$

$$(II) \quad \nabla p_e = n_e(-m_e g - eE)$$

subtracting, $(I) - (II) \approx 0$, so that $E = (\frac{M_i}{2e})g$. Now we can go beyond Pannekoek and Rosseland:

The electric field in a stellar (fully ionized plasma) atmosphere in itself does not induce currents. This field, however, is proportional to gravitational acceleration. That *implies that if* g *changes*, *so does* E:

$E \propto g \Rightarrow \dot{E} \propto \dot{g}$!

But how could $\dot{g} \neq 0$?

Close Encounters

The answer is surprisingly simple. Although average distances between stars are very large, close encounters can happen. When sufficiently close, gravity at the stellar surface facing the other star will diminish, even to the extent that tidal bulges can appear. This is simply ebb and flood. While the affected star rotates, and the “intruder” is getting closer and then moving away, the bulges change their position on the star, so does the disturbed charge distribution, but both stay on the orbital plane defined by the relative motion of the stars.

Conclusion

The induced magnetic dipole is normal to the orbital plane. It follows that the probability distribution of obliquity is proportional to Sinus(obliquity). That accounts for *larger obliquity preference*. Individuality of Oblique Rotator properties (e.g. amplitude, obliquity, inclination, location in space, type of star involved) depend on a whole list of parameters, such as space density of stars, relative mass, impact parameter and type of orbit, parabola or hyperbola. We conclude that close stellar encounters, changing local gravity, can eventually induce the generation of Oblique Rotator magnetic fields, and are identified as the dynamo. Once there, in the absence of convection, the fields are permanently fossilized into the stellar atmosphere. Thus, Dynamo and Fossil models are *both relevant*.

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Table 1. *Frequency Distribution of Obliquity Angels.J. Power, 2007*

Obliquity (degrees)	number of stars
0 – 10	5
10 – 20	3
20 – 30	1
30 – 40	1
40 – 50	2
50 – 60	3
60 – 70	4
70 – 80	5
80 – 90	6