DYNAMO ACTION IN LATE-TYPE GIANTS

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Abstract

Recent numerical MHD simulations suggest that magnetic activity may occur in late-type giants. A red supergiant with stellar parameters equal to Betelgeuse was modelled in 3d with the high-order “Pencil Code”. Linear and non-linear saturated dynamo action are found and the non-linear magnetic field saturates at a super-equipartition value, while in the linear regime two different modes of dynamo action are found. Magnetic activity of late-type giants, if it exists, may influence dust and wind formation and possibly lead to the heating of the outer atmospheres of these stars.

Key words: Stars: AGB, activity, Betelgeuse

1. Introduction

Both recent theoretical and observational advances indicate that late-type giant stars may possess magnetic fields. It has been suggested that non-spherically symmetric planetary nebulae form during late stages of AGB star evolution as a result of the collimating effect of magnetic fields. From observations, maser polarisation is known to exist in circumstellar envelopes of AGB stars (e.g. Gray et al. 1999, Vlemmings et al. 2003, and Sivagnanam 2004) and X-ray emission has been observed from some cool giant stars (e.g. Hülsch et al. 1998 and Ayres et al. 2003). These observations are generally taken as evidence for the existence of magnetic activity in late-type giant stars (cf. Soker & Kastner 2003).

The cool star Betelgeuse is a much observed late-type supergiant that displays large-scale surface structures (e.g. Gray 2004). Freytag et al. (2002) performed detailed numerical 3-d simulations of the convective envelope of the star under realistic physical assumptions, while trying to determine if the star’s known brightness fluctuations may be understood as convective motions within the star’s atmosphere: The resulting models were successful in explaining the observations as a consequence of giant-cell convection on the stellar surface. Dorch & Freytag (2002) performed a kinematic dynamo analysis of the convective motions in the above model and found that a weak seed magnetic field could indeed be exponentially amplified by the giant-cell convection.

This is a report on recent full non-linear MHD simulations of dynamo action in a late-type supergiant star with fundamental stellar parameters set equal to that of Betelgeuse (see also Dorch 2004).

2. Model

The full 3-d MHD equations was solved for a fully convective star so that the entire star is contained within the computational box. The computer code used is the “Pencil Code” by Brandenburg & Dobler (see also Dorch 2004). This is a report on recent full non-linear MHD simulations of dynamo action in a late-type supergiant star with fundamental stellar parameters set equal to that of Betelgeuse (see also Dorch 2004).

Dynamo action by flows are sometimes studied in the limit of increasingly large magnetic Reynolds numbers Re_m = ℓ/U/η, where ℓ and U are characteristic length and velocity scales, and η is the magnetic diffusivity. Most astrophysical systems are highly conducting resulting in a small magnetic diffusivity η, and their sizes are huge yielding enormously large values of Re_m. Betelgeuse is not an exception, and most parts of the star are better conducting than the solar photosphere that has η ≈ 10^4 m^2/s. Taking ℓ to be 10% of the radial distance R from the centre, and U to be an estimate of the RMS speed along the radius yields Re_m = 10^10–10^12 in the interior of the star.

In the present case we cannot use that large values of Re_m, but rely on the results from generic dynamo experiments showing that overall results converge already at Re_m of a few hundred (e.g. Archontis, Dorch, & Nordlund 2003b, 2003a). Here we use a value of η leading to a magnetic Reynolds number of Re_m ~ 300.

1 http://www.nordita.dk/data/brandenb/pencil-code/
3. Discussion of results

Figure 1. Simulated surface intensity snapshots at four different instants, time = 256, 347, 457 and 494 years (from upper left to lower right).

Though it is not the topic of this contribution, it is appropriate to discuss the properties of the convective flows in the model, since these ultimately supply the kinetic energy forming the basic energy reservoir for magnetic activity. It is not expected that the flows match exactly what is found in more realistic radiation simulations, but at least a qualitative agreement should be inferred.

Large scale convection develop rapidly throughout the star and is evident in several variables: However, since the model does not incorporate realistic radiative transfer, only a simulated intensity can be derived: Figure 1 shows simulated intensity snapshots at different instances. The contrast between bright and dark patches on the surface is 20–50%, and only 2–4 cells are seen at the stellar disk at any one time. The simulated intensity is in qualitative agreement with the models of Freytag et al. (2002): The surface is not composed of simply bright granules and dark intergranular lanes in the solar sense—the large-scale convective patterns are typically larger than 15–30% of the radius, and are actually often on the order of the radius in size. The corresponding radial velocities range between 1–10 km/s in both up and down flowing regions.

Once the convection is taking place the magnetic field is amplified and the system enters a linear regime of exponential growth. There are two modes of amplification in the linear regime: An initial mode with a growth rate of about 4 years, which in the end gives way to a mode with a smaller growth rate corresponding to a time-scale of about 25 years.

Figure 2. Transition to the non-linear regime: RMS magnetic field in the whole computational box as a function of time in years. The upper curve is the equipartition field strength corresponding to the average kinetic energy density of the fluid motions (dotted curve) and the lower full curve is the actual RMS field strength (full curve). The dashed thin curve correspond to growth times of 25 years and a horizontal reference line at 100 Gauss.

Figure 3. Energy spectra of the magnetic energy density (solid curve) and kinetic energy density (dashed curve) at time = 512 years, and a line corresponding to a power-law with an exponent of -2/3 (dashed-dotted line). The vertical lines, from left to right, denote the wavenumbers corresponding to the computational box size, the stellar radius, and the numerical resolution.

No exponential growth can go on forever and eventually the magnetic energy amplification must stop: The question is whether the magnetic field retains a roughly constant saturation value, or if it starts to dissipate. In
case of saturation the typical field strength is likely to be on the order of the equipartition value corresponding to equal magnetic and kinetic energy densities. Figure 2 shows the magnetic field strength $B_{\text{RMS}}$ within the entire star as a function of time for $\sim 800$ years: The second linear mode as well as the mode in the non-linear regime are visible. The magnetic field saturates at a value slightly above the equipartition field strength $B_{\text{eq}} = \sqrt{\mu_0 \langle \rho u^2 \rangle} \sim 90–100$ Gauss, corresponding to a value of about 120–130 Gauss. In terms of total energy this corresponds to magnetic energy $E_{\text{mag}}$ being above equipartition with the kinetic energy $E_{\text{kin}}$ by roughly a factor of two. Hence the field is not extremely strong, but is neither particularly weak. From the observational viewpoint the strength of the field at the surface is interesting. In the non-linear regime the field strength at the sphere at $r = R$ can be up to $\sim 500$ Gauss, while in the interior of the star the field strength rises and can be as high as a few kG: The strongest magnetic structures completely quenches the velocity field in these regions, i.e. the local field can be far above equipartition. The downward increase of the field strength is similar to the flux pumping effect found in the solar context (cf. Dorch & Nordlund 2001).

Energy spectra reveal that the magnetic structures are well resolved, and that the power at the largest wavenumbers $k \sim 100$ is a few orders of magnitude smaller than that at the largest scales (see Figure 3). The power is maximum on the largest scales corresponding to wavenumbers of a few, while there is a dip at $k \sim 7$ corresponding to the scale of the radius, where the power is minimum. The power on scales $k \approx 10–20$ is roughly proportional to $k^{-2/3}$ corresponding to Kolmogorov scaling, and at small-scales $k \gtrsim 50$ the power steeply drops: Magnetic structures in the non-linear regime are then large by solar standards, but smaller than the convection cells.

![Figure 5. A 3-d volume rendering of magnetic field lines (white) and flux ropes (dark structures). Also shown is a isosurface (transparent) at the surface temperature value.](image)

The geometry of the magnetic field in the saturating non-linear stage of the dynamo may since this could be relevant for the influence of the field on the formation of asymmetric dust and wind: The field is concentrated into elongated relatively thin structures, but forms no intergranular network.
4. SUMMARY AND CONCLUSION

Three different modes of dynamo action are recognised: A fast growing linear mode with a growth time of $\sim 4$ years, a relatively slowly growing mode with an exponential growth of $\sim 25$ years, and finally a saturated non-linear mode operating a factor of two above equipartition. More modes may exist, but they must have very low growth rates or very small amplitudes since they have not appeared in the simulations.

On the one hand, it is not possible to state conclusively if Betelgeuse actually has a magnetic field, on the basis of the present model, since such a field is unobserved. On the other hand, one can state that it seems possible that late-type giant stars such as Betelgeuse may have presently undetected magnetic fields. These fields are possibly close to equipartition yielding surface strengths up to 500 Gauss. The latter field strengths may be difficult to detect directly, due to the relatively small filling factors of the strong fields, but even the moderately strong fields may influence their immediate surroundings.

Finally it is note worthy that Lobel et al. (2004) recently published spatially resolved spectra of the upper chromosphere and dust envelope of Betelgeuse. These observations reveal that the chromosphere extends far beyond the circumstellar envelope. The presence of a hot or warm chromosphere may lead one to speculate on the possible connection to coronal heating in solar-like stars, which is magnetic in origin and caused by flux braiding motions in the photosphere (Gudiksen & Nordlund 2002). It remains to be studied whether a similar process could be taking place in late-type giants.

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