STELLAR ASTROPHYSICS

Polarization from a spinning star

Although predicted 50 years ago, the polarization of light from a rotationally distorted stellar atmosphere has only recently been detected, thanks to polarimetry measurements with precision at the parts-per-million level.

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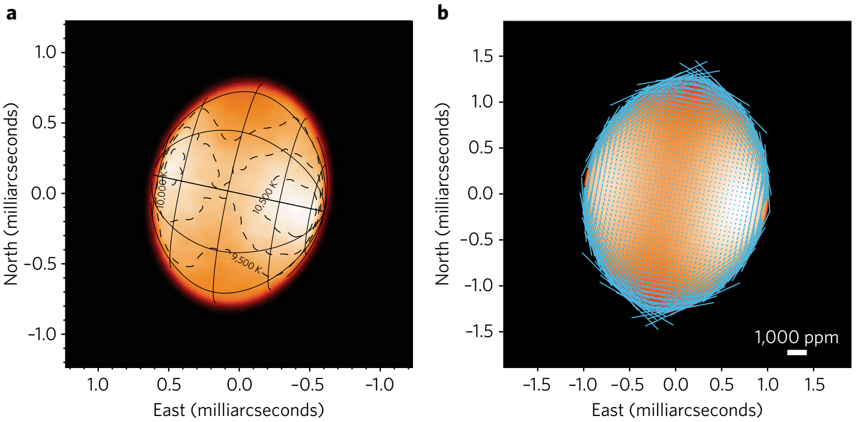

Fig. 1 | Reconstructed image and polarization model of Regulus. a, Surface brightness and shape of Regulus, determined by interferometry[7]. Dashed lines are surface temperature. **b**, Stellar model showing polarization vectors arising from the stellar atmosphere[1] (cyan lines). Panels reproduced from: **a**, ref. [7], IOP; **b**, ref. [1], Macmillan Publishers Ltd.

Often an effect is predicted long before it can be measured: the detection of gravitational waves is an outstanding instance. Now, writing in *Nature Astronomy*, Daniel Cotton and collaborators[1] report the measurement of an effect predicted nearly 50 years ago, which had long seemed beyond the reach of observation. The authors have measured the faint polarization that arises within the atmosphere of a hot star: the rapidly spinning (320 km s^{-1}) B7V star, Regulus.

Scattering of radiation by free electrons in a hot stellar atmosphere will cause the emergent radiation to be partially polarized. If we could resolve the star, the radiation from any point on the stellar disc would show polarization either perpendicular or parallel to the radial line from the centre. Usually, spherical symmetry demands that, when integrated over the whole stellar disc, the net polarization will average to zero. A rotating star, however, is not spherical. Furthermore, the rotation will result in a surface temperature gradient from the pole to the equator. These effects break the symmetry and lead to a net polarization of the starlight.

Based on Chandrasekhar's solution for a pure electron-scattering atmosphere, in 1968 George Collins and I calculated the expected net polarization for hot stars[2]. We found it could reach about 1% for stars rotating near their break-up velocity. Later, when more realistic model atmospheres replaced the pure scattering atmosphere, the net polarization expected at optical wavelengths turned out to be orders of magnitude less[3]. Such small values of net polarization seemed to be immeasurable.

In the intervening years, remarkable advances have been made in instrumentation. As we are dealing with a differential measurement of radiation with polarizers in different orientations, there is no fundamental limit to the precision possible as long as there are enough photons, and switching orientation is faster than any atmospheric changes. In 2005–2006, the PlanetPol instrument made initial measurements of a number of bright stars[4]. Among stars within our local bubble, Regulus showed anomalously high polarization. Subsequent measurements of this star were made at other wavelengths with the High Precision Polarimetric Instrument (HIPPI)[5], which switches the orientation of the optical axis at 500 Hz. The accuracy achieved with this instrument on the 3.9-m Anglo-Australian Telescope is ~4 parts per million (ppm) for bright stars. Cotton et al. find that the polarization of Regulus varies almost linearly with wavelength from +42 ppm at 741 nm to −22 ppm at 395 nm. The change of sign indicates a change in the direction of the polarization vector by 90°.

This change in the direction of the polarization as we go from short to long wavelengths is key; it has long been predicted for hot stellar atmospheres[3,6]. The direction of polarization depends on the gradient of the Planck function with optical depth. When an electron scatters light, the polarization is greatest for scattering through 90° and the scattered light is polarized perpendicular to the plane of scattering. At short wavelengths (near the peak of the Planck function), radiation is mostly streaming upwards from the hot, deeper layers of the star. When we observe the limb of the star, we see radiation has been scattered in a plane perpendicular to the stellar surface. But at longer wavelengths, emission depends less on temperature (the Rayleigh–Jeans limit), and hence on optical depth. Thus near the surface, there may actually be more radiation travelling horizontally than vertically. Radiation moving horizontally will be scattered in a plane that is parallel to the surface and therefore there can be a reversal in the sign of the polarization as we go from blue to red. No such effect would be expected if the scattering was occurring above the atmosphere in circumstellar material.

To make quantitative comparisons with theory, the authors[1] have first modified the ATLAS9 stellar atmosphere code to output not only intensity but also polarization. Then, for a chosen stellar rotation velocity, they calculate the shape of the star and the pole-to-equator variation in gravity and temperature. Thus at each point they can construct a model atmosphere for the local gravity and effective temperature and compute the spectrum an observer would see from that surface element. Integration over the observed surface then provides the net polarization seen by a distant observer. Now Regulus, at a distance of 24.3 pc, has been spatially resolved by interferometric observations[7]. Thus we know its shape, the orientation of its rotation axis and the variation of its surface temperature with latitude (Fig. 1a). Cotton et al. found that the observed polarization vectors agree with the axis known from interferometry. They obtain an excellent fit to the magnitude and wavelength dependence of the polarization for a model rotating at 96.5% of its break-up velocity. Figure 1b shows the brightness and polarization vectors for this model at a wavelength of 400 nm. Surface temperature varies with latitude on a rotating star: the Cotton et al. models use a modern temperature law[8], which agrees well with the measured intensity distribution[7] and empirically rules out the classical von Zeipel temperature law.

This work is important not just for validating some (non-controversial) aspects of radiative transfer in stellar atmospheres. It heralds the arrival of high-precision polarimetry as a tool for stellar astronomy. It is significant that this first polarization modelling of Regulus provides a more precise determination of the angular velocity of this star than interferometry or spectroscopy. The structure and evolution of stars with rapid rotation is a complex and as yet unsolved problem[9]. Observational input, such as that provided by polarization studies, will be necessary for progress.

We should also note that polarization measurements of the precision demonstrated here are approaching the level that can be expected to contribute to the study of exoplanets. Exoplanet transits break the symmetry of the star, giving rise to a polarization signature, while hot giant exoplanets might reveal their presence through polarized Rayleigh scattering of the incident stellar illumination. ❐

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