Line profile variations in γ Equ: A puzzle

Hiromoto Shibahashi[1], Don Kurtz[2], Eiji Kambe[3], Douglas Gough[4]

[1]*Department of Astronomy, University of Tokyo, Tokyo 113-0033, Japan*
[2]*Centre for Astrophysics, University of Central Lancashire, Preston PR1 2HE, UK*
[3]*Department of Earth and Ocean Sciences, National Defence Academy, Yokosuka, Kanagawa 239-8686, Japan*
[4]*Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK*

Abstract. Line profile variations in γ Equ show the classic blue-to-red travelling bumps of m-modes resolved by rotation, and they have been identified as $\ell = 2$ or 3, $m = -\ell$ or $-\ell+1$ by characterising the line shapes using the moment method. The mode identifications cannot be correct, however, since γ Equ is an extremely slowly rotating star ($P_{rot} > 70\,yr$). We propose an alternative interpretation, according to which the observed line profile variations are a manifestation of a shock wave in the high atmosphere near the magnetic polar regions; the oscillation mode is then still consistent with the photometric observations.

1. Introduction

The rapidly oscillating Ap (roAp) stars are cool magnetic Ap stars with periods in the range 6–16 min; there are currently 32 known members of the class. In many cases, the amplitude of the light variations is modulated with the rotational period of the star, as is the apparent magnetic field strength. To explain this phenomenon, Kurtz (1982) proposed the oblique pulsator model, in which the pulsation is interpreted as axisymmetric ($m = 0$) dipole ($\ell = 1$) oscillations, whose symmetry axis coincides with the magnetic axis which is itself inclined to the rotational axis.

The amplitude of such axisymmetric modes is large in the polar region of the symmetry axis. As the star rotates, the aspect angle of the pulsation (and the magnetic axis) varies; hence the apparent pulsation amplitude varies synchronously with apparent magnetic strength during a rotational period. This model has been theoretically investigated and has been refined substantially. Though the model is still phenomenological, it has explained many photometric observational features of roAp stars (for reviews see, e.g., Kurtz & Martinez 2000; Shibahashi 2003).

Since the atmospheres of Ap stars are expected to be horizontally chemically inhomogeneous, it is expected that by using spectral lines of various elements one can get information on the spatial character of the eigenfunctions and, hopefully, identify the modes. High-resolution spectroscopic observations are required for this purpose, and recently some striking new observational results

287

have been reported (Savanov, Malanushenko, & Ryabchikova 1999; Kochukhov & Ryabchikova 2001a,b; Balona & Zima 2002; Kochukhov et al. 2002; Balona 2002; Balona & Laney 2003; Kurtz, Elkin, & Mathys 2003; Kurtz et al. 2003).

Kochukhov & Ryabchikova (2001a) found spectacular line profile variations (LPV) for γ Equ in lines of Nd III and Pr III. Based on an application of the moment method of quantifying the variability in the line profile (Balona 1986a, 1986b; Aerts, De Pauw & Waelkens 1992), they interpreted the observed line profile variations as being caused by oblique pulsation modes of $\ell = 2$ or 3 and $m = -\ell$ or $-\ell + 1$. This result is in disagreement with the oblique pulsator model interpretation that the photometric variations are caused by low-ℓ, axisymmetric modes. The observed LPV move only from blue-to-red as seen in Kochukhov & Ryabchikova's (2001a) Fig. 1. This common pattern has been previously observed in rapidly rotating B stars pulsating in sectoral modes (e.g., Balona et al. 2002), and it is this feature that led Kochukhov & Ryabchikova (2001a) to their interpretation.

When a star undergoes nonradial oscillation, different parts of the stellar surface move at different phases and this kind of motion produces a particular characteristic variation of line profile when combined with stellar rotation. However, γ Equ has virtually no rotation ($P_{\rm rot} > 70$ yr; Leroy et al. 1994), hence there is no significant rotational broadening of the spectral lines for this star, and the situation is quite different from the case of rapidly rotating B stars. In the case of a non-rotating star, the modes suggested should show LPV that move through the line from blue-to-red, then back again, as demonstrated in Fig. 1 for the case of $\ell = 2$. The mode identifications suggested by Kochukhov & Ryabchikova cannot be correct.

The LPV also cannot be caused by sectoral-like modes resolved by the pulsation wave pattern speed for modes such as those envisaged in Bigot & Dziembowski's (2002) improved oblique pulsator model, since the periods of γ Equ are near 12.4 min, so the wave pattern moves with a speed of about 10^4 km s^{-1} – far too high to be relevant here.

2.   A new interpretation

The familiar blue-to-red LPV in γ Equ cannot have the familiar rotationally resolved m-mode explanation. There is no rotation. The problem is thus to explain why the LPV show such monotonic blue-to-red movement, while the photometric observations imply axisymmetric dipole oscillations, from which blue-to-red-to-blue LPV are expected. We propose here an alternative interpretation for the observed LPV.

Kochukhov & Ryabchikova's (2001a) Fig. 1 indicates that the Nd III λ 6145 line-forming layer is moving with a maximum speed of 18 km s^{-1} in one pulsation cycle. This maximum speed is much higher than the radial velocity pulsation amplitudes so far detected from other spectral lines in other roAp stars – of the order of 1 km s^{-1} or less (Libbrecht 1988; Kanaan & Hatzes 1998). This is possible if the Nd III λ 6145 line is formed in a high layer where the density is very low. Actually, Ryabchikova et al. (2002) estimated that this line is formed in a thin layer at the very low optically depth $\tau_{5000} \simeq 10^{-8}$.
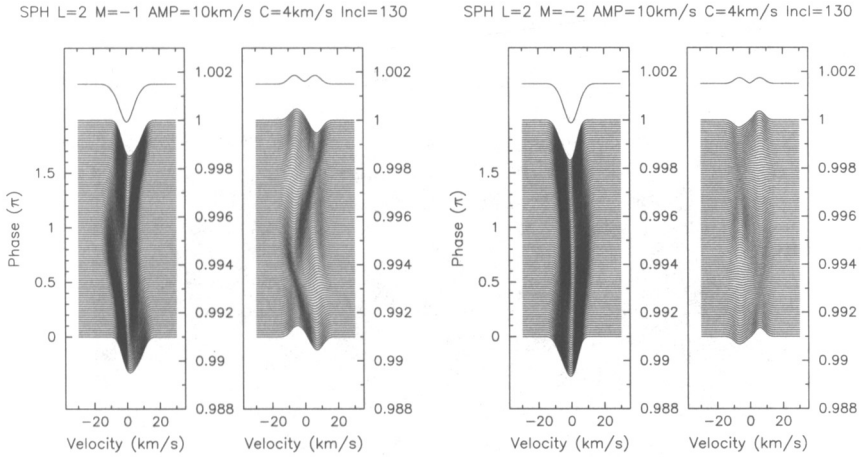
Figure 1. Theoretically expected LPV due to an $\ell = 2$, $m = -1$ mode (left) and an $\ell = 2$, $m = -2$ mode (right) for a non-rotating star. The pulsation amplitude is assumed to be $10 \, \mathrm{km \, s^{-1}}$ and the line profile is assumed to have an intrinsic line width corresponding to a velocity of $4 \, \mathrm{km \, s^{-1}}$. The aspect angle between the pulsation axis and the line-of-sight is assumed to be 130°. For each mode the LPV for one pulsation cycle are shown on the left panel, and the difference between the LPV and the average profile (shown top left) are displayed in the right panel. Clearly, the LPV move from blue to red and back again, not just from blue-to-red. The top of the right panel for each mode shows the standard deviation.

The important point is that this maximum speed seems to be faster than the sound speed of the atmosphere. The pulsation amplitude in velocity is expected to increase with the decrease of the density with height. So the amplitude in velocity naturally exceeds the sound speed at a certain level, and a shock wave is generated. When this shock wave propagates through the layer under consideration, the layer is suddenly kicked upward by the shock wave and then falls down after reaching the peak height, at which the speed of the layer is zero. This process repeats and the resultant variation in the Doppler shift is qualitatively in agreement with the observed one in Nd III line of γ Equ. The lack of variation in the standard deviation in the middle of each cycle occurs as the layer comes to a stop, then falls back.

This picture may also be consistent with the mode identifications from the photometric observations, which imply axisymmetric dipole modes whose symmetry axis coincides with the magnetic axis, both being inclined to the rotation axis of the star. If it is correct, then following are expected: 1) The LPV should be sinusoidal for the spectral lines formed in layers where the wave motion is subsonic; 2) The LPV should be sinusoidal for chemical elements that are not concentrated in the magnetic polar regions, so their pulsation velocities remain sub-sonic; and 3) The LPV should show monotonic blue-to-red motion only for the lines formed in the high atmosphere near the magnetic polar regions.

It should also be noted that the photometric observations of many roAp stars have nonlinear features (Kurtz 1990).

This interpretation can be tested observationally by detailed investigation of LPV of various spectral lines. High spectral resolution, high time resolution, high S/N spectroscopic observations are definitely desired. They will certainly improve our understanding of physics of roAp stars.

References

Aerts, C., De Pauw, M., Waelkens, C. 1992, A&A, 266, 294

Balona, L.A. 1986a, MNRAS, 219, 111

Balona, L.A. 1986b, MNRAS, 220, 647

Balona, L.A. 2002, MNRAS, 337, 1059

Balona, L.A., Laney, C.D. 2003,MNRAS, 344, 242

Balona, L.A., Zima, W. 2002, MNRAS, 336, 873

Balona, L.A., James, D.J., Motsoasele, P., Nombexeza, B., Ramnath, A., van Dyk, J. 2002, MNRAS, 333, 952

Bigot, L., Dziembowski, W.A. 2002, A&A, 391, 235

Kanaan, A., Hatzes, A.P. 1998, ApJ, 503, 848

Kochukhov, O., Ryabchikova, T. 2001a, A&A, 374, 615

Kochukhov, O., Ryabchikova, T. 2001b, A&A, 377, L22

Kochukhov, O., Landstreet, J.D., Ryabchikova, T., Weiss, W.W., Kupka, F. 2002, MNRAS, 337, L1

Kurtz, D.W. 1982, MNRAS, 200, 807

Kurtz, D.W. 1990, ARA&A, 28, 607

Kurtz, D.W., Martinez, P. 2000, Balt. Astron., 9, 253

Kurtz, D.W., Elkin, V.G., Mathys, G. 2003, MNRAS, 343, 5

Kurtz, D.W., Mathys, G., Elkin, V., Martinez, P., Anguma, S., Kalebwe, P., Kebede, L. 2003, in ASP Conf. Ser., Vol. 216, International Conference on Magnetic Fields in O, B and A Stars, ed. L.A. Balona, H.F. Henrichs & R.S. Medupe (San Francisco: ASP), in press

Leroy, J.L., Bagnulo, S., Landolfi, M., Landi Degl'Innocenti, E. 1994, A&A, 284, 174

Libbrecht, K.G. 1988, ApJ, 330, L51

Ryabchikova, T., Piskunov, N., Kochukhov, O., Tsymbal, V., Mittermayer, P., Weiss, W.W. 2002, A&A, 384, 545

Savanov, I.S., Malanushenko, V.P., Ryabchikova, T.A. 1999, Astron. Letters, 25, 802

Shibahashi, H. 2003, in ASP Conf. Ser., Vol. 216, International Conference on Magnetic Fields in O, B and A Stars, ed. L.A. Balona, H.F. Henrichs & R.S. Medupe (San Francisco: ASP), in press
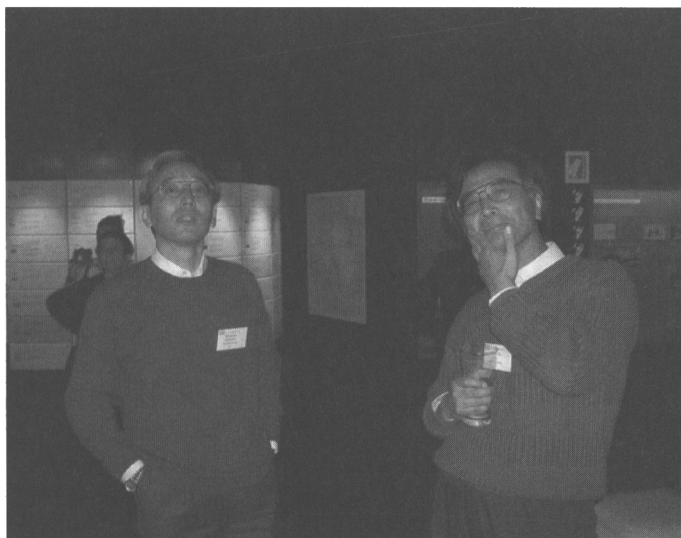
Hiromoto Shibahashi and Hideyuki Saio
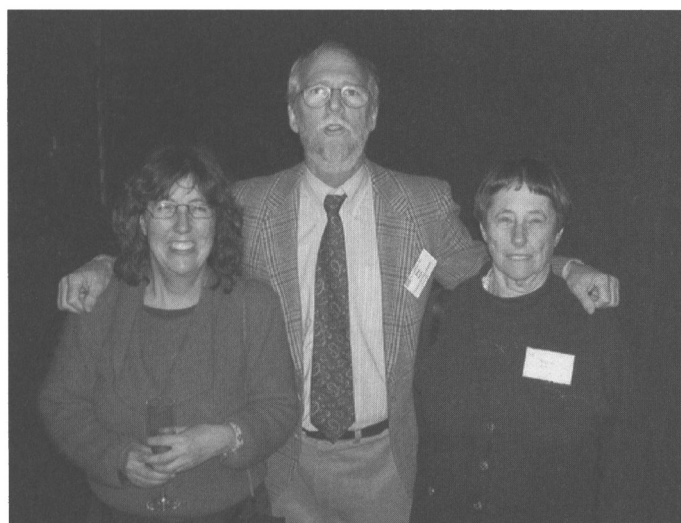
Jean Wehlau, Don Kurtz and Amelia Wehlau