The Variable Star ET Andromedae - a Tidally Excited Pulsator? ⋆

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Abstract. Spectroscopic observations of the B9p star ET And secured at the Bulgarian National Observatory Rozhen in the years 1981-1984, show clearly a radial velocity period of 0.198 d - with a ratio to the photometric period of exactly 2:1. This behavior would hint at a close binary system with tidal bulges. Considering the excitation of pulsations, then the eigenfrequency of a nonradially pulsating star would be in agreement with the physical parameters of the star. Obviously, the pulsation appears as a wave running around the star and beeing in resonance with an orbiting companion.
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Key words: Chemically peculiar stars, light and radial velocity variations, pulsation, tides, star: ET And

1. Introduction - observational facts

Among the observational facts of the variable B9 star ET And (HD 219749) that have been gathered, and which are summarized by SCHOLZ and GERTH (1990), there prevails, as a striking feature, the exact ratio of 1:2 between the periods of the radial velocity and the brightness variations. The phase relations between these variations have been measured simultaneously only once in 1981 during three nights yielding nearly coincidence of light minima and radial velocity extrema. The maximal variation in brightness amounts to $\triangle m$ = 0.02 mag, and in radial velocity to $\triangle v$ = 3.5 km/s (Fig. 1 after GERTH et al. 1984a).

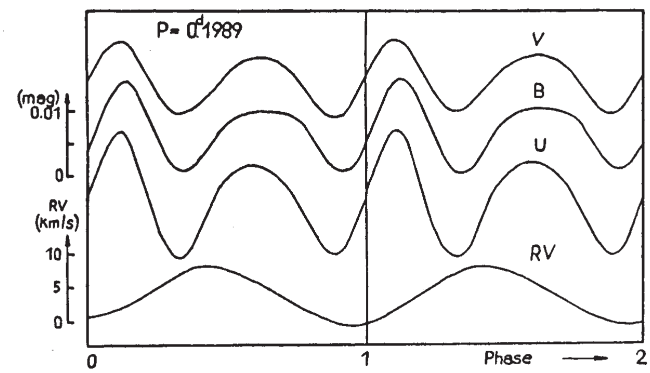

Fig. 1 Phase relation between the variations of the U, B, V magnitude and the radial velocity at the period of 0.1989 days. The curves are derived by Fourier analysis and optimization using only the first 3 harmonics.

2. Models of the star

There have been made different attempts to explain these facts by hypothetical models (GERTH et al. 1984a; SCHOLZ et al. 1985; GERTH et al. 1984b; GERTH 1986), but they do not satisfy because either the quantitative conditions or the frequency and phase relations do not accord. A first suggestion for an explanation is given, obviously, by the supposition of a close binary system. All seems to fit very well; however, awkward difficulties arise if we try to calculate such a system quantitatively. The hardest point is the very short

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period of the radial velocity of P = 0.1989 d having to be attributed to the revolution. Taking the mass of the B9III star from a mass-luminosity function (SCHOLZ et al. 1990), we have $M = 4.2M$ corresponding to a radius of $R = 5.5R_\odot$. With these values of P and M we obtain a (circular) orbital radius $R = 3.31R_\odot$, smaller than the radius of the star itself.

To overcome this contradiction, one could think about an eclipsing binary with two gravity centers close together and a common envelope. We do not investigate the question whether such an exotic stellar system could have been generated at all; but asking for the stability against fast rotation and inserting the given parameters, clear evidence emerges for the impossibility of existence. Even considering the most favorable case with the gravity centers of the two stars concentrated in one point, avoiding thus any elongation, we obtain with $P = 0.2$ d at the distance of $R = 5.5R_\odot$ the equatorial velocity v = 1392 km/s, which exceeds the velocity of escape v = 381 km/s. The system would be disrupted.

In any case the period of 0.2 d is too short for the binary model. Stellar and orbital radii would coincide only at a period of P = 0.73 d, which is nearly four times the observed period.

3. The pulsator model

Another explanation of the observational facts can only resort to pulsations. An estimation of the possible periods and modes has been given by SCHOLZ et al. (1990). However, it is quite unclear, what the reason for the excitation of pulsations might be. Therefore, a distinction between the radial and nonradial modes has to be made on the basis of the observational material. We shall see later whether this could be possible.

Usually only internal sources are held responsible for the excitation of pulsations in stars. Internally excited oscillations, of course, should not be excluded in the case of ET Ind. But oscillations of the stellar surface can also be excited by external forces like tides. The well established companion of ET And with the orbital period of 48.30 d and the eccentricity 0.46 could perhaps affect the surface of the main star because of its changing distance and inhomogeneous gravity field. In principle, even small and for their own not observable stellar bodies in the neighborhood of the main star like planets may invoke tides, especially if resonance is present.

4. The eigenfrequency of a pulsator

Let us consider first the star as an oscillation system like an organ-pipe! The eigenfrequency of the pipe is determined by its length and the speed of sound, thus depending likewise on density and temperature of the air as the oscillating medium.

The eigenfrequency of an oscillating star has been derived in a plausible analogous way by KAPLAN (1982), who used HUYGEN's pendulum formula. Inserting for the pendulum length l the stellar radius R and for the acceleration $g = GM/R^2$ (at the distance R from the center with the mass M of the star and the gravitational constant G), we obtain

$$\omega = \sqrt{\frac{g}{l}} = \sqrt{\frac{GM}{R^3}} \quad or \quad P = 2\pi\sqrt{\frac{R^3}{GM}}, \tag{1}$$

which is identical with that one for the frequency of a probe body revolving around a star on an orbital radius $r = R$.

The product of the period and the square root of the mean density $\overline{\varrho}$ of the star comes out as to be a constant,

$$P\sqrt{\overline{\varrho}} = \sqrt{\frac{3\pi}{G}} = \text{const.} \tag{2}$$

The formula holds well and is proved experimentally by observations at cepheids; the constant, however, has to be changed from 0.122 to a value between 0.4 and 0.6 (units: g, cm, d). Say, the constant be 0.5, then we have a factor approximately 4. This is referred by KAPLAN to the fact that the oscillations take place in the interior of the star, so that the effective radius has to be reduced.

We can use a similar approach to find the eigenfrequency of the surface layer of the star as an oscillating system. A probe body with the mass m located at the surface would be attracted to the center of the star by the force

$$F = \frac{GMm}{R^2}, \tag{3}$$

which stands in equilibrium against the pressure of the gaseous interior of the star. Oscillations take place around the zero-position at R. The repulsing force is given by differentiating equation (3),

$$\triangle F = -\frac{2GMm}{R^3}\triangle R = -D\triangle R, \tag{4}$$

D being the direction magnitude of the oscillation, from which the eigenfrequency is easily to be derived,

$$\omega = \sqrt{\frac{D}{m}} = \sqrt{\frac{2GM}{R^3}}. \tag{5}$$

If we, moreover, take into account, that not only the surface but the whole star oscillates, then we have to reckon with some kind of an average stellar radius, which is determined geometrically by the density stratification within the star and the motion conditions of the oscillation. Choosing arbitrarily for the most intensively oscillating part of the stellar interior the distance $R/2$ from the stellar center, we have

$$\omega = 4\sqrt{\frac{GM}{R^3}} \quad or \quad P = \frac{\pi}{2}\sqrt{\frac{R^3}{GM}}. \tag{6}$$

This formula (6) gives the factor 4, which has to be added to the simple pendulum formula (1) after KAPLAN. Some more precise calculations accounting for the density distribution may vary this factor anyhow, but do not affect the approximate magnitude.

Returning in our consideration to the star ET And, we obtain, using equation (6), with $M = 4.2M_\odot$ and $R = 5.5R_\odot$, the period $P = 0.182$ d being in good agreement with the measured period of 0.2 d. Therefore, we conclude that pulsation is the very probable phenomenon we observe at ET And.

5. The excitation mechanism of pulsations

For our decision what kind of excitation mechanism might be valid at ET And, already simple considerations suffice. Referring the analogy to the organ-pipe, we see two possibilities of excitation: the airstream producing curls at the lip of the pipe or streaking the open end. The first possibility we may call with view to the star the "internal excitation" and the other one the "external excitation". The source of energy for the internal excitation of pulsations in stars are nuclear reactions occurring in the deep interior of the star or in spherical shells surrounding the center in a certain distance. In any case the transfer of energy is radially symmetrical, so as the excitation must have the radial direction, too, leading to preferentially radial modes of pulsation.

Radial pulsations are accompanied by periodical contractions and expansions of the entire surface uniquely. Therefore, the light and radial velocity variations must have the same period, i.e. the exact ratio 1 : 1.

Nonradial pulsations possess also tangential components to the radial direction that do not affect the mentioned frequency ratio. The energy source for excitation can be located either inside or outside the star, whereby an asymmetric arrangement has to be taken into account. As we have no grounds to presume such an inner asymmetry, we should seek for influences onto the star from outside.

The energy for the external excitation is contributed only by other stellar bodies such as companions, planets, satellites etc.

In rare cases it may be the consequence of an interstellar encounter. The star as an oscillating system is capable to maintain the oscillating state for a long time depending on the degree of damping.

A nonradial oscillation cannot be confined locally on the star's surface, for all parts represent coupled oscillators; that means, the oscillation must propagate through the star or along its surface as a wave.

6. The wave model

The imagination of a wave running around the star's surface is quite attractive, for it gives immediately an explanation of the frequency ratio $1:2$ observed at ET And. The crest of the wave produces a bulge on the surface conducting to a behavior as it is known for an ellipsoidal star. Therefore, during one period, a variable cross section of the two photospheres is turned towards the observer. It has, naturally, to be questioned, whether the speed of propagation of such a circulating wave in the star fits to the observed period.

The physics of waves is rather complicated. But taking a look into a manual we find a similarly simple approach as that we carried out above. The essential point is that waves on surfaces of liquids propagate as well in the longitudinal as in the transversal mode simultaneously whereas the liquid elements perform circular motions around an axis perpendicular to the direction of propagation with a speed c that depends on the gravitational acceleration g and the height h of the surface over the ground by

$$c = sqrtgh. \tag{7}$$

If we wind up the track of one wave to a circuit, then the ground shrinks to a single point - the center of the star. The velocity of the wave emerges from the periphery of the circuit $2\pi R$ and the period P, the acceleration at the height $h = R$ being $g = GM/R^2$, then we have

$$\frac{2\pi R}{P}\sqrt{\frac{GM}{R}} \qquad or \qquad P = 2\pi\sqrt{\frac{R^3}{GM}}, \tag{8}$$

which is completely the same relation as equation (1). Therefore, we concluded that the wave circulates with exactly the pulsational eigenfrequency or, more precisely, the oscillation migrates around the periphery of the star by the eigenfrequency. In this way wave migration and revolution around the star coincide formally, and it is no wonder that the binary model fits well in all points except the orbital radius, which would be too small.

But the problem of the small radius has been overcome by the wave model. The effective radius, moreover, may be even smaller than the stellar radius. If the wave goes through the middle parts of the interior between center and surface at $R/2$, then we obtain exactly equation (6), which fulfills the observational results at ET And.

The other parts in the neighborhood of the main stratum, which determines the eigenfrequency, take part in the undulation with a characteristic phase shift, which follows from the circular motion of the elementary parts but much the more by the different propagation velocities in the stratification of the increasing density in dependence on the depth from the surface to the center of the star.

Thus the upper strata retard in phase but, being in resonance, swing in the same rhythm. By this way also the phase shift between light and radial velocity variations, as shown in Fig. 1, finds a plausible explanation.

7. A proof of the wave model

A complete proof can be given only by consideration of all observational results in comparison with the expected phenomena without contradiction. We restrict this consideration here to only one point that seems us very important, namely the elongation of the star, due to the tidal bulge, like an egg.

For the expansion of the radius we use the formula

$$\triangle R = v_{max} \cdot \frac{P}{2} \cdot \frac{1}{\sqrt{2}} \cdot \Pi \cdot \frac{1}{\sin i}, \tag{9}$$

wherein Π stands for the integral over the projected elements of the hemisphere. Inserting the observed value of v_{max} = 3.5 km/s (Fig. 1) we obtain $\triangle R/R$ = 0.0175 = 1.75%.

The same projection on the line of view is valid for the light variation. With the well-known magnitude-formula we have

$$\triangle I = I\,(10^{0.4\triangle m} - 1)\frac{1}{\sin i}, \tag{10}$$

which yields with the maximal value $\triangle m = 0.02$ likewise $\triangle I/I =$ 0.018 = 1.8%.

8. Conclusions

All signs hint at a high probability of the wave model for the star ET And. The excitation mechanism is not clear yet, bat we can say that it could be understood as an exchange of energy and impulse in portions every period at periastron passage of the 50-day companion. The energy transferred should be sufficient to maintain the excited oscillation and to drive the wave in direction of the passage. By dissipation of energy the system falls automatically in resonance making the excitation more effective.

Theoretical investigations of the transfer and excitation mechanism as well as quantitative calculations have still to be made.

Urgently needed are more reliable observations, especially in the phase of periastron passage. There is, for instance, indicated an extension of the period at periastron because of the presence of a further gravitational center in the vicinity of the star.

ET And, of course, might not be the single star suspected to perform wavelike pulsations. If excited waves circulating the star are typical for a sufficiently close binary system, in particular with a highly eccentric orbit, then we could find similar phenomena at related other objects, that we should **seek** for!

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