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ANALYSIS OF THE LIGHT CURVE OF THE RV TAURI STAR LV Del

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The RV Tauri star LV Del was observed by the Indiana University 0.41 meter automated photometric telescope (a.k.a., Roboscope) from 1990 to 2003, and was first noted by Honeycutt et al. (1992). The V magnitude light curve of LV Del is presented in Figure 1, and consists of 1263 data points acquired from JD 2448420 through JD 2452919. We have reduced the light curve using the method of ensemble photometry on an inhomogeneous data set (Honeycutt, 1992), and the error bars represent the uncertainty of the differential photometry. The zero point has an uncertainty (standard deviation of the mean) of 0.006 mag, determined using standards from the field of HR Del (Henden & Honeycutt, 1997), in which LV Del lies.

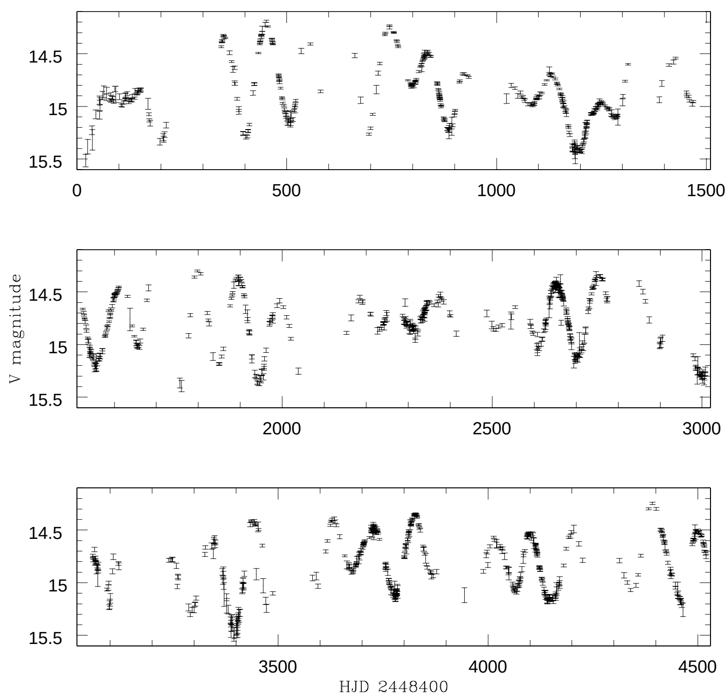

Figure 1.

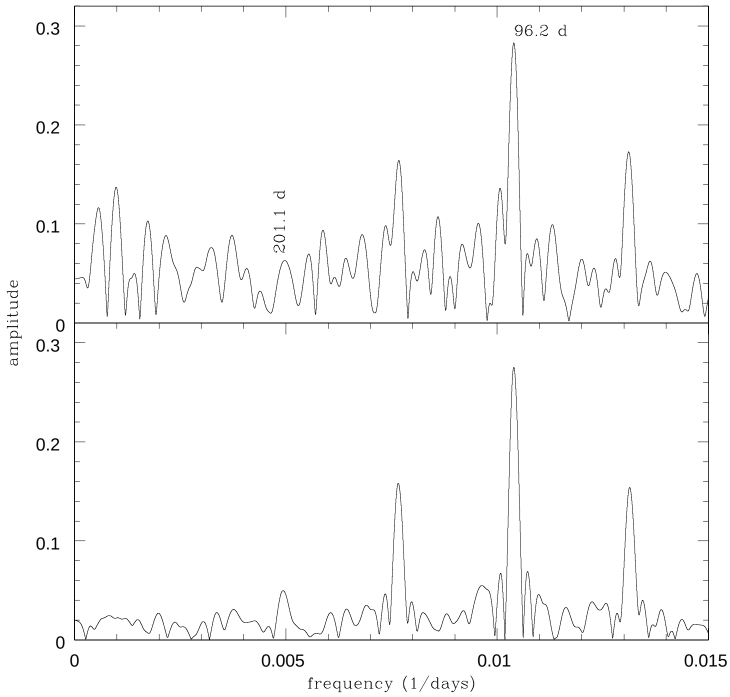

Figure 2.

A Fourier transform of the data, presented in the top panel of Figure 2, gives 96.2d as the dominate period. To demonstrate spectral leakage and aliasing, in the bottom panel we present a FT of a sine wave having the same period and amplitude; this wave has been evaluated at the same JDs as the actual light curve. Visual inspection of the light curve indicates that the 96.2d signal is not the "formal" RV Tauri period, but rather is the first harmonic, implying a value of 192.4d for the formal period. Visual inspection also suggests that the traditional RV Tauri "double hump" feature corresponding to the formal period is poorly expressed after about 1996 - 1997. The appearance of the light curve after this point is "Cepheid-like", which is one of the typical irregularities exhibited by RV Tauri stars (Tsesevich, 1975); this apparent behavior is quantitatively supported by the dominance of the first harmonic in the FT, while no significant peak corresponding to the predicted formal period appears to present.

In order to test for any systematic changes in the period (another irregularity noted by Tsesevich, 1975), we have applied Fourier transforms to the light curve in two year overlapping windows (i.e., 12 such windows were used). A least squares fit to the resulting values of the first harmonic period versus time gives a rate of 0.10 ± 0.27 day/year, indicating no significant change in period.

Visual inspection of the light curve of LV Del suggests two other phenomena of interest: first, there appears to be a long term systematic variation of the mean brightness; second, there appears to be variation in the amplitude of the first harmonic, on a similarly long time scale. We examine the first in the top panel of Figure 3, which plots the mean brightness for one whole cycle out of each year of data (with error bars representing the standard deviation of the mean), along with a sinusoidal fit. Note that points for 1997 and 1999 have been omitted due to the data being more sparse in those years. The variations are larger than the errors, thus substantiating the presence of this signal, and identifying LV Del as a member of RVb photometric subclass (i.e., those exhibiting such long term variations; see, e.g., Tsesevich, 1975). The fitted sinusoid has a period of 1636.3d, a mean magnitude of 14.79, and an overall amplitude of 0.24 mag. Visual inspection suggests that these variations are not in fact strictly periodic, which is not uncommon for RVb stars (Tsesevich, 1975; Fokin, 1994). Two low frequency peaks, at 1762d and 1017d, also suggest the presence and irregularity of such a signal. It has been proposed (Tsesevich, 1975; Fokin 1994) that the secondary variability of the RVb class may be due to their being a member of a binary system in which they are periodically eclipsed by the ejection shell of the companion star.

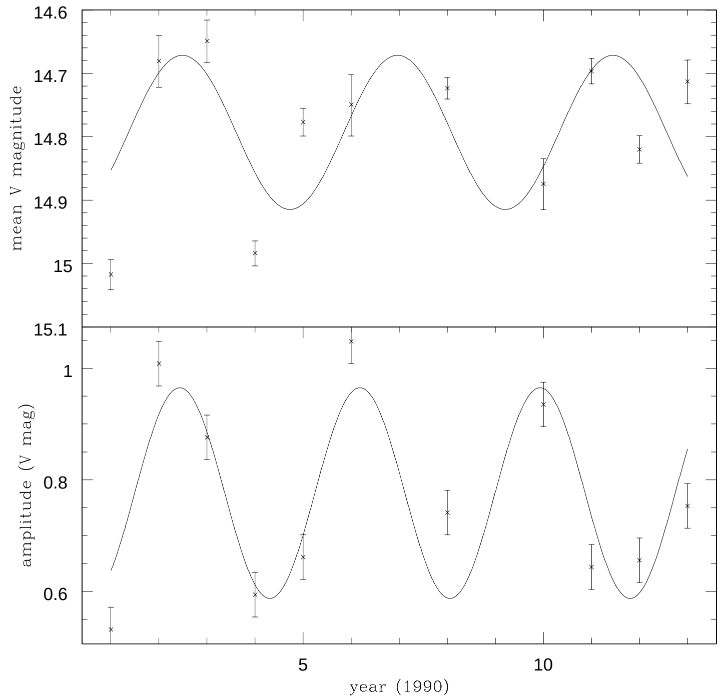

Figure 3.

To examine the apparent variation in pulsational amplitude, in the bottom panel of Figure 3 we plot the average amplitude for the same cycles as used for the top panel (in magnitudes; again, 1997 and 1999 have been omitted), with typical errors, and again with a sinusoidal fit. The errors are significantly smaller than the variations, thus verifying the presence of this variation in amplitude. The sinusoid has a period 1369.3d, where as that in top panel has a period of 1636.3d, and lags that in bottom panel by a phase of 3.7 years. For some RVb stars, these two variations are in phase (Tsesevich, 1975). In the case of LV Del, if we compare the data points in the two panels, we see that they appear to be in phase only during roughly the first half of the data set; however, the sinusoid fits indicate that, on average, the two variations are not in phase. This apparent shift in the behavior of the light curve is roughly correlated with the shift to Cepheid-like behavior mentioned above. If the star is in fact a binary, this correlation could support the idea that RVb stars are close binary systems, as proposed by Fokin (1994), which might allow a physical correlation between the pulsation and the binary nature.

The chaotic nature of the light curves of the RV Tauri stars AC Her (RVa) and R Sct (RVb) has been established (Kolláth et al., 1998; Kolláth, 1990). We have tested for chaos in the light curve of LV Del using the TISEAN non-linear time analysis package (Hegger et al., 1999). Note that this analysis was performed using a spline-smoothed light curve, with one day spacing, in order to insure uniform spacing and to maximize the available information, given that the non-linear time series analysis is very sensitive to noise. Following the procedure of Kiss & Szatmáry (2002), we used the TISEAN package to generate a phase space reconstruction of the data, and used the resulting phase space vectors to generate Broomhead-King projections of the phase space. The presence of intersections and cusps appeared to be minimized for an embedding dimension of 4, and so we may take this as a tentative indicator of the embedding dimension of the phase space (see, e.g., Kolláth et al., 1998). However, the projections were quite noisy, and no significant structure was apparent. Given the high data density of both the real and smoothed light curves, this is an indication that the data set is simply too short to obtain informative results. In this regard, we may compare to the data of Kolláth (1990), Kolláth et al. (1998), and Kiss & Szatmáry (2002) who had data sets of 32 years, 150 years, and 100 years, respectively.

A quantitative measure of the chaos present in a signal can be achieved by calculating the maximal Lyapunov exponent, which is a measure of the exponential growth of the infinitesimal perturbations which lead to chaos (Hegger et al., 1999). If chaos is present the maximal exponent should be positive (e.g., Kiss & Szatmáry, 2002). Again using the procedure laid out by Kiss & Szatmáry (2002), we have used the TISEAN package to calculate the maximal Lyapunov exponent, finding a value of 0.0238 ± 0.0031, which quantitatively indicates the presence of chaos. Again note that the spline-smoothed light curve was used.

The analysis herein has identified LV Del as an RV Tauri star of the RVb subclass. Although the formal period is poorly expressed, the irregularities exhibited by this star are typical of RV Tauri stars. The change in the behavior of the amplitude variations from being in phase to being out of phase with the long term variations in mean brightness may be correlated with the change to Cepheid-like behavior exhibited in the light curve, but we can only speculate as to the physical origin of either effect. The positive value of the maximal Lyapunov exponent indicates the presence of chaos in the light curve, but this must be taken with caution, as a longer data set would provide more certain results (see, e.g., Kiss et al., 1998). The Broomhead-King projections of the phase space trajectories suggest that the light curve is embedded in a low-dimension phase space with an embedding dimension of $\sim$4, but this is only tentative.

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