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Activity cycles in UX Arietis

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Abstract. By analysing long term radio observations of the binary system UX Arietis, activity cycles have been discovered which are strongly reminiscent of those present in the Sun. It is well known that the activity cycle in the Sun is 11 years, while the general magnetic field reverses every 11 years, returning to its initial configuration after 22 years, namely after two consecutive cycles of activity. Now we have discovered in UX Arietis an activity cycle of 25.5 days during which the polarization reverses and returns to its initial value after about two consecutive cycles of activity. Moreover as the cycle of 11 years of the Sun is modulated with a period of 90-110 years, poorly estimated due to its long term occurence, we found that the 25.5 days activity cycle in UX Arietis is also modulated with a period of 158 days. The solar activity cycle is related to the dynamo at work in the sun's interior. The fact of having in UX Arietis the same phenomena as in the Sun but at much shorter time scales (i.e. days instead of years) should make possible to acquire better statistics in the future and improve our understanding of the dynamo processes.

Key words: stars: individual: UX Ari – stars: activity – stars: magnetic fields – radio continuum: stars

1. Introduction

UX Arietis is a binary system formed by a spotted K0 IV primary and a G5 V secondary having a 6.44 days orbital period. Vogt and Hatzes (1991) discovered that the spot distribution is rather stable and proved that the spotted star has a differential rotation. Such a rotation, together with the presence of a convection zone, much deeper than that of the Sun, are the necessary ingredients for a very efficient dynamo mechanism, responsible for the high activity of the system (for references see Elias et al. 1995).

An observing campaign dedicated to the UX Arietis binary system has been performed with the 100-m radiotelescope at Effelsberg (Neidhöfer et al. 1993) with the main purpose of obtaining information on possible systematic trends of the stellar activity that may be important for a better understanding of the dynamo process.

In this paper we present the analysis of the data collected during a period of 965 days. In the next section we present the data set observed in the whole period and we determine the possible periodicities of the stellar activity, using two different statistical methods discussed in the Appendix. Light curves are obtained by folding the data with different periods. In Sect. 3 we discuss the light curve obtained by folding the data with the orbital period. In Sect. 4 we present a very good fit to the whole dataset obtained with a suitable periodic function. A possible periodicity in the percentage polarization is considered in Sect. 5. Summary and conclusions are presented in Sect. 6.

2. Periodicities

UX Arietis has been observed with the Effelsberg 100-m telescope over a frequency range spanning from 1.4 GHz (21 cm) to 43 GHz (7 mm) collecting a total number of 269 samples over a period of 965 days. The set of data obtained is presented in Fig. 1 as a function of the Julian Day. The data are plotted together with their error bar. For detail on the observations we refer to Neidhöfer et al. (1993).

Inspection of Fig. 1 clearly shows that large flares (S $\geq$ 250mJy) are only observed at high frequencies. In order to check whether the activity shown in Fig. 1 presents any periodicity, we have analyzed the whole data set using two independent methods of period determination together with a simulation procedure. This data processing, described in detail in the Appendix, has given as a result a dominant period at 25.5 days and two other periods at 14.4 and 158.7 days. A further check of the spectral analysis is supplied by the plots of the data as a function of phase for each determined period. The data folded with a given period will cluster around a specific phase when the periodicity is real, while, if there is no periodicity, they will appear uniformly scattered at all phases.

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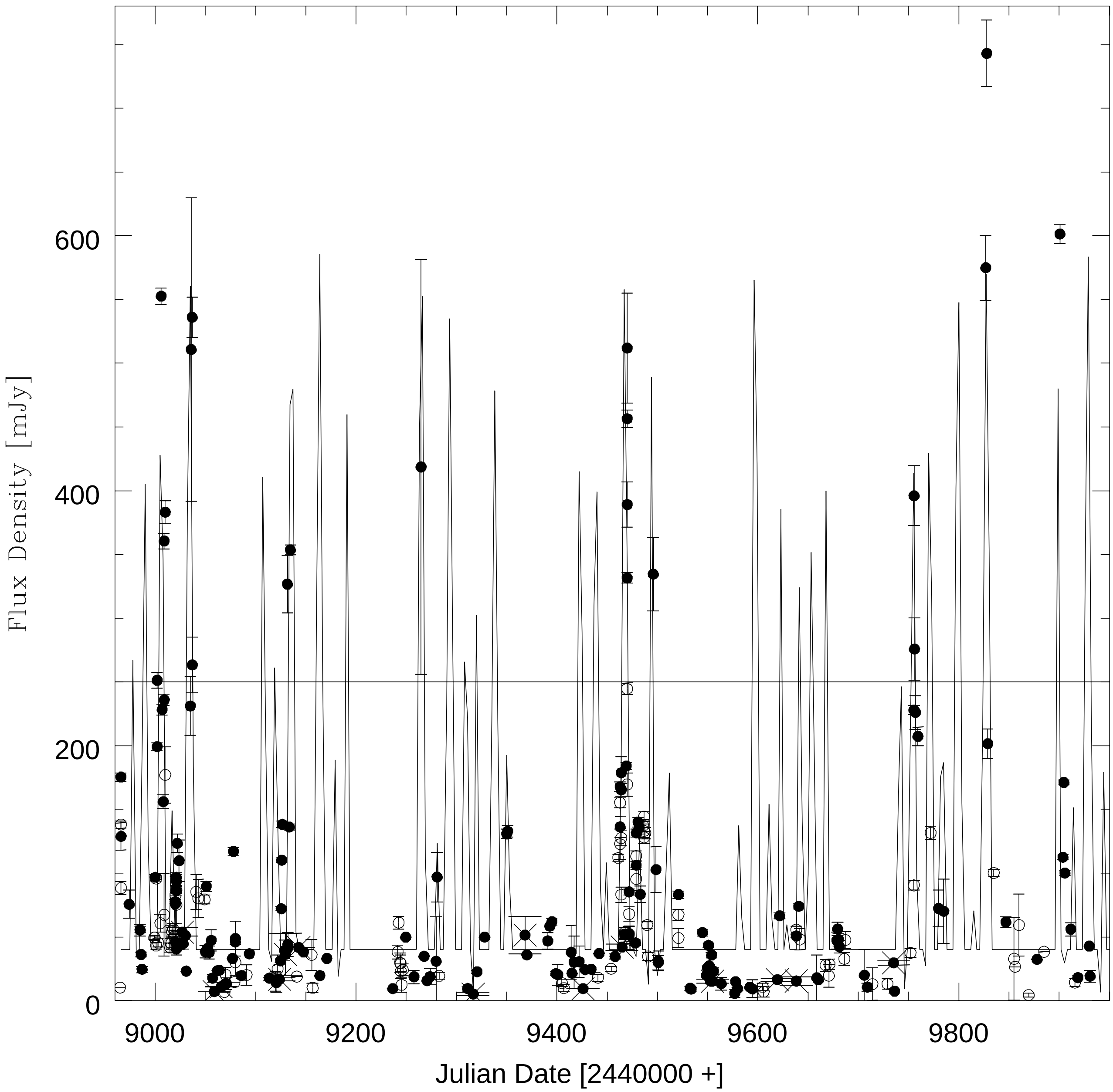

Fig. 1. Observations with the Effelsberg 100-m telescope. Dots indicate frequencies higher than 5.4 GHz; open circles frequencies lower than that. The continuous line shows the model fit and crosses show the occurrence of the periodic shadowing (see Sect. 4)

The data, plotted in Fig. 2, indicate a clear periodicity, shown by the considerable cluster around phase 0.8, when folded with the 14.4 days period and around phase 0.1 when folded with the 25.5 days period.

The data folded with the long term period of 158.7 days appear to cluster in a different way: they recall a square wave rather than a sinusoidal trend as in the two preceeding plots. In this step function the upper level lasts longer (0.5-1.1) than the lower one.

3. Rotational modulation of the radio emission

A very interesting result appears when we plot versus phase the data folded with a period equal to the orbital one, of 6.44 days, as shown in Fig. 3 (note: due to the synchronism this is the rotational period as well). Together with a general scatter of the data, indicating that the stellar activity is not related to the orbital period, this plot shows an evident hole of activity around phase 0.4. During the whole period of observations it was in fact noticed that the flux underwent sudden decreases when approaching the orbital phase 0.4. This decrease was of course much more evident if the star was flaring at that moment.

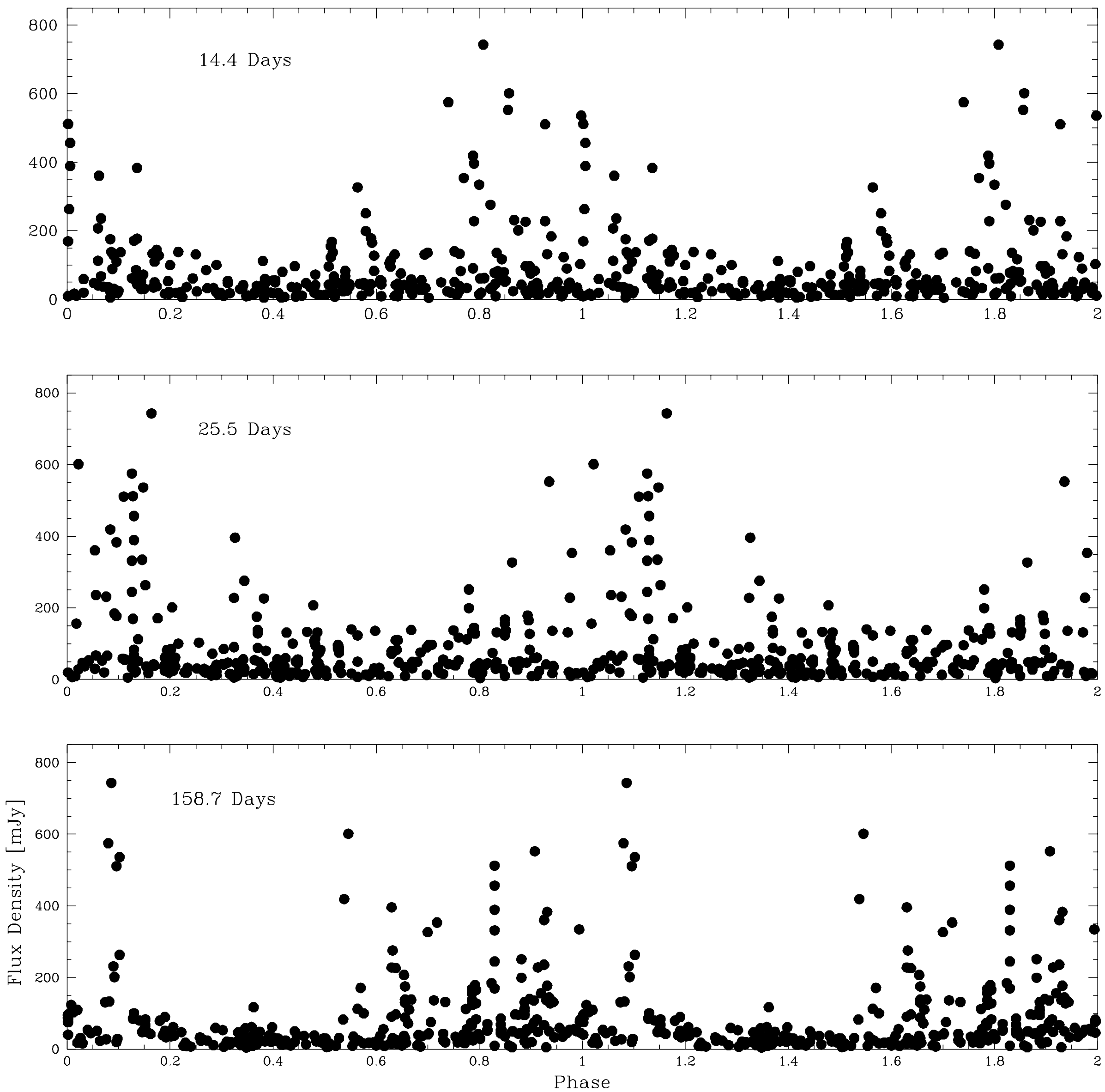

Fig. 2. Radio light curves produced by folding the data with the specified periods. The phase interval 0-1 is repeated twice

During the phase interval between about 0.35-0.45 the observed flux values never exceeded 50-100 mJy, irrespective of the value observed before entering in this phase interval. This effect cannot be attributed to absorption by material between the two stars as already pointed out by Trigilio et al (1996) who observed the same phenomenon at λ =6 cm.

It is known (Klein and Chiuderi Drago, 1987; Franciosini and Chiuderi Drago,1996) that, due to the magnetic field gradient in a magnetic loop, the radio emission at a given frequency is generated at a height increasing with decreasing frequency. Radio emission at high frequencies is therefore coming from the loop legs while the low frequency flux is coming from the loop top. Since the hole appearing in Fig. 3 is particularly evident for the high values of the flux, which, as already mentioned, are observed only at high frequencies, the only explanation for such a sudden flux decrease can be the disappearence of the corresponding source (i.e. the loop legs) behind the star. In other words such a minimum can be interpreted (Massi et al. 1996) by taking into account the 6.44 days rotation of the active star together with a two-component model for the emitting region: a component, compact enough to be oscured by the body of the star during each rotation and responsible for the high (up to 750 mJy) level of emission, and an extended component, always visible, responsible for the 50-100 mJy at phase 0.4. We note, in passing, that such a two-component model has been indeed observed by VLBI (Mutel et al. 1985). The extended component could be associated with the highest part of the loop, or alternately to a larger magnetized volume within the binary system filled by fast electrons escaped from the energy release site (Beasley and Bastian, 1997).

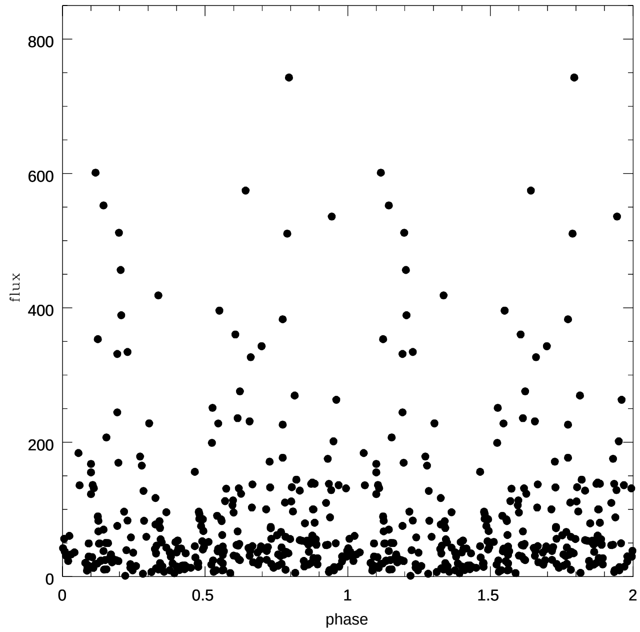

Fig. 3. Radio light curve produced by folding the data with the rotational period of 6.44 days. A minimum is discernable at phase 0.4.

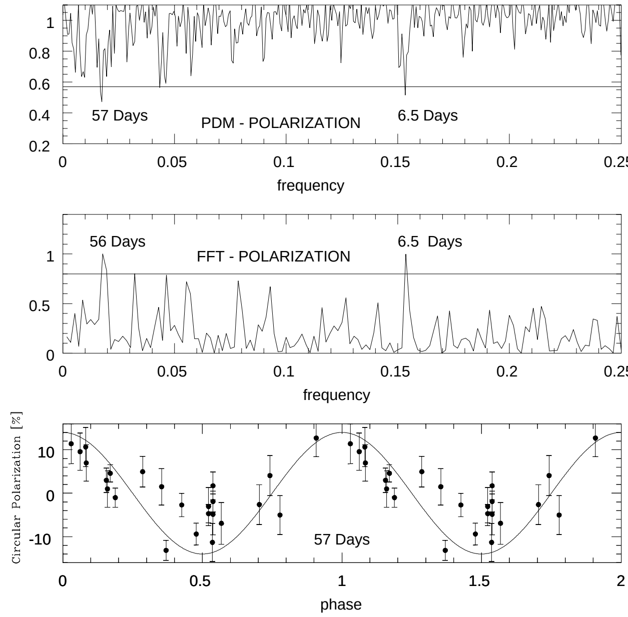

Fig. 4. Spectra by FFT and PDM for the circular polarization. Bottom: circular polarization data folded with a period of 57.14 days

A very important result connected with the presence of this hole of activity at a particular phase is the stability in longitude of the stellar activity for 965 days. We recall here that at phase 0.5 the other star (a G5 V star), of this non eclipsing binary system, is between us and the active K0 star. As previously shown, around this phase the active region is located in the non visible side of the K0 star, consequently the preferred longitude on the K0 star for developing flares is in the hemisphere opposite to that facing the G5 V star. That the magnetic fields of the two stars might interact in the intervening medium has often been assumed by many authors after Uchida & Sakurai (1983) first advanced such an hypothesis. Our finding that no flare develops on the side facing the G5 V component could be the observational proof for a modified topology of the magnetic field between the two stars preventing any activity.

4. Fitting the whole data set

In this section we summarize in one equation, able to reproduce the real set of data shown in Fig. 1, the results here described. We assume that the star oscillates between two states of activity: on and off. The step function is assumed to have a period of 158.7 days. During the off state the flux is assumed to be 40 mJy. During the on state (phase 0.5-1.1) the emission is modulated as:

$$225\cos\left[2\pi\left(\frac{\Delta t}{25.5}-0.1\right)\right]+325\cos\left[2\pi\left(\frac{\Delta t}{14.43}-0.8\right)\right]+40. \quad (1)$$

where $\Delta t = t - t_0$ with t_0 = 92440133.766 JD (Carlos and Popper 1971).

The shadowing due to the star rotation has also been taken into account by reducing the flux to 40 mJy whenever in excess of this value. The crosses in Fig. 1 correspond to phases 0.35-0.45 of the orbital period.

It appears from Fig. 1 that the computed curve fits the data points remarkably well, reproducing the time of occurrence of all flares above 250 mJy. Of course the intensity of each flare cannot be reproduced by this type of fit as it depends on many unpredictable variables, such the magnetic field strength in each loop and its orientation with respect to the observer, the number and the energy spectrum of the emitting particles, etc.

5. Circularly polarized radio emission

Some of the observations of our sample also contain measurements of the left hand (LHC) and right hand (RHC) circular polarizations. From these data we have selected only those with error bars lower than 5%. Moreover, according to Mutel et al. (1985), only the low level emission is polarized, therefore we have rejected, from the polarization data set, all data having a total flux density larger than 100 mJy.

The spectral analysis results are shown in Fig. 4 (see Appendix for details). Two relevant periods are present: one at 6.5 days in both spectra and one at 57 $\pm$ 4 days in the PDM analysis and at 56 $\pm$ 4 in the FFT one. The peak at 6.5 days is clearly related to the stellar rotation and can be easily explained in the following way. The longitudinal component of the magnetic field in the top of a non meridian loop changes sign at any central meridian transit of the loop. The electrons spiralling along these field lines are therefore alternately producing LHC and RHC polarization during each half rotation. The period of 12.88 days, previously determined by Neidhöfer et al (1993) on a subset of the present data was therefore a subharmonic of the 6.44 day period.

While the 6.5 days period is due to a purely geometric effect, that at 57.14 days could be related to the magnetic field activity. It is in fact, within their error bars, twice the 25.5 day period previously determined. In the lowest panel of Fig. 4 the observed polarization percentages, plotted versus phase, turn out to be well represented by a sinusoidal curve of P = 57^d.

6. Summary and conclusion

In the present paper we have shown that the dynamo mechanism present in the active star of the UX Arietis binary system presents two alternating "regimes"; the active and the quiescent one, with a total period of 158.7 days. The duration of the active state seems to be 20% longer than that of the quiescent one.

During the active phase the activity does not take place randomly, but shows a periodical trend with two periods of 14.4 and 25.5 days.

Sudden flux decreases at $\nu > 5.4\ GHz$ which always take place at the same orbital phase, are ascribed to the disappearence of the radio source behind the star.

The sign of the circular polarization seems to reverse within the dominant activity cycle of 25 days, returning at its initial value after 56 ± 4 days. If this polarization reversal is due to a polarity inversion of the general field of the star, this is strongly reminiscent of what happens on the Sun. It is very well known that the solar activity is cyclical with a period of 11 years, while the general magnetic field of the Sun (and hence the polarity of the preceeding and following spots in the spots groups of each hemisphere) reverse every 11 years, returning at its initial configuration after 22 years, namely after two consecutive cycles of activity.

We would like to point out that these sequences of very active periods followed by quiescent ones, confirm the predictions of theoretical models on the existence of two different convective states with a different angular velocity distribution (Tobias et al 1995). Such a theory has so far been applied only to the Sun, where the activity cycle of 11 years (22 years taking into account the magnetic field polarity) appears to be modulated with a period of about 90 years. According to recent observations of the average sunspot numbers (Mouradian and Soru-Escaut,1995), the long term periodicity modulating the 11 years cycle seems to have increased its period to about 110 years. The statistical relevance of those observations is however limited, since only two such long term periods in the solar activity ihave taken place since 1770! This fact increases the interest of the results presented in this paper, since they may provide a way of constructing more reliable statistics to compare with the predictions of dynamo theories having the same phenomenon at much shorter time scale: 158 days for UX Arietis instead of more than one hundred years as in the case of the Sun.

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Appendix A

The Fast Fourier Transform (FFT) spectrum of the data of Fig. 1 is shown in Fig. 5. Above 4 σ (the drawn line) a number of 8-10 features are present. However our sampling is rather irregular. Therefore we have complemented the Fourier analysis with another method of period determination: the PDM. The PDM method (Phase Dispersion Minimization, Stellingwerf 1978) is efficient to use on irregularly spaced data (as ours) and ideally suited to highly nonsinusoidal time variations. It is simply an automated version of the classical method of distinguishing between possible periods: a light curve for each trial period is obtained and the scatter of the observations computed. The most likely periods are those that produce the least observational scatter: in correspondence to these periods we will therefore observe minima in the spectrum, contrary to what happens with the FFT analysis, where the most likely periods appear as maxima. In the top panel of Fig. 5 the results of the two methods are plotted one above the other. The horizontal lines indicate the 4σ level for each method: only those peaks simultaneously exceeding these lines (below it for the PDM and above it for the FFT analysis) are here considered.

Among the 8-10 periods found by FFT only 5 of them agree, within their error bars ($\Delta P = P^2$ 0.0014 days) with those determined by PDM, those at: **14.3**±0.3 days (14.4±0.3 for PDM), **24.1**±0.8 (25.5±0.9 for PDM), **34**±2 (33.2±1.5 for PDM), **39**±2 (36± 2 for PDM) and at **71**±7 days (75 ±8 for PDM).

The dominant period for both methods is that at 25 days; the order of importance of the other periods is unclear. Moreover some periods could be subharmonics of dominant periods, like that at 71 days which seem to be a multiple of that at 14 days. In order to identify among the five periods the dominant ones we have applied the two methods, PDM and FFT, to artificial data: merely a sum of sinusoidal functions sampled at our observing points without noise added. Assuming only the minimum combination of two periods, one of the two that of 25 days, we have tried the 4 combinations of it with the other 4 periods. The sum of two sinusoidal functions at 25 and 14 days has revelead to be the successful combination; the only one, as shown in the lowest panel of Fig. 5, able to reproduce the results shown in the upper panel of Fig. 5. The peaks at 34, 39 and 70.9 days (33.2, 35.7 and 75.1 days by PDM) are determined as well in the spectra of the artificial data and therefore can be discarded as dominant periods. In particular we note that the peak at 34 days (at 33 days in the PDM) is only the result of a beat of the two main frequencies (i.e. 1/33=1/14.4- 1/25.5).

In conclusion, by using the PDM and artificial data we could establish that among the many features present in the FFT spectrum only the two at 25.5 and at 14.4 days are meaningful.

The period present in the PDM analysis at 158.7 days, although not present in the FFT analysis, is worthy of special attention because a long term periodicity clearly affects the data of Fig. 1. As shown in Sect. 2 of this paper, this periodic vari-

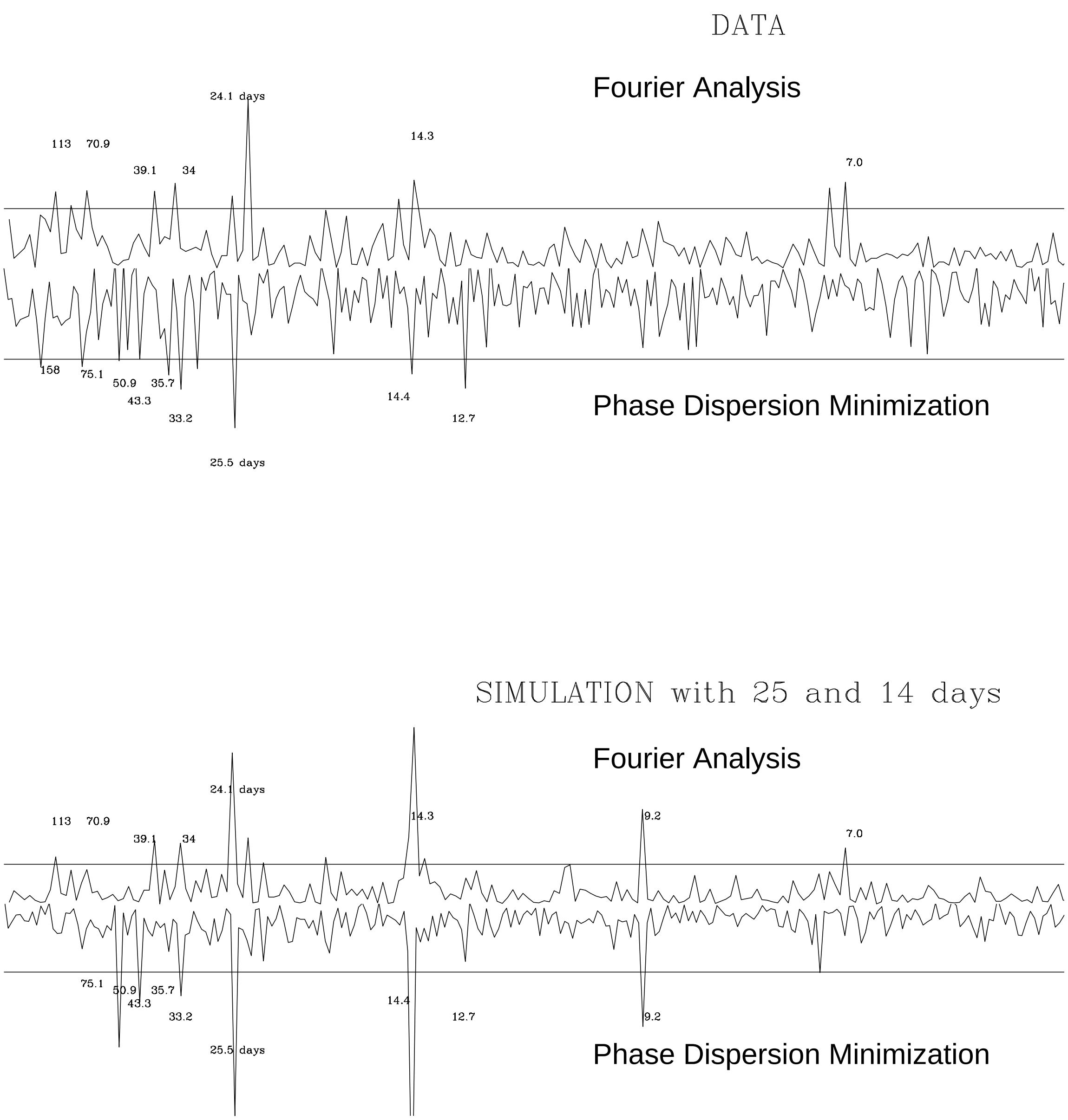

Fig. 5. Spectra by FFT and PDM for observations and artificial data

ation has a square wave trend rather than sinusoidal one. This explains why it is determined by the PDM, which is, as mentioned above a method "ideally suited for highly nonsinusoidal time variations"(Sterllingwerf, 1978).

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