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Observational Asteroseismology of slowly pulsating B stars

P. De Cat

Koninklijke Sterrenwacht van België, Ringlaan 3, 1180 Brussels, Belgium

Abstract

We review the status of observational asteroseismology of slowly pulsating B (SPB) stars. Their asteroseismic potential is extremely good because the excited high-order g-modes probe the deep interior of these hot stars. To enable asteroseismic modelling, a sufficient amount of well-identified modes is mandatory. To reach this goal with ground-based observations, dedicated long-term and preferably multi-site campaigns are needed to increase the number and the accuracy of detectable frequencies. The first results for SPB stars based on observations obtained with the asteroseismic space-mission MOST are very promising, guaranteeing the success of missions like CoRoT, launched in December 2006. These results also indicate that high-precision observations are needed to detect and to study low-amplitude SPB stars. Although SPB pulsations are not restricted to slow rotators, there is some observational evidence for an amplitude drop towards high values of the projected rotational velocity. For several SPB stars, close frequency multiplets are observed. In some cases, the observed frequencies might be components of a rotationally split mode, but in other cases an alternative explanation is needed. Magnetic fields of a few hundred Gauss, that recently have been detected for fourteen confirmed members, can cause such frequency shifts. SPB stars can no longer be considered as non-magnetic stars and magnetic fields should be included in the theoretical models. We argue that mode identification of g modes still remains one of the main obstacles, although progress has been made in this field recently.

Asteroseismic potential

After conducting a systematic study of variability amongst B type stars, Waelkens (1991) introduced the slowly pulsating B (SPB) stars as an independent class of stars pulsating in high-order, low degree gravity modes (g modes) with typical periods of the order of days. These modes are excited by the opacity mechanism acting on the metal-bump. They are trapped deep in the interior of these hot stars, making them very interesting from an asteroseismic point of view. On the other hand, they are very difficult targets for in-depth asteroseismic studies because the theoretical frequency spectra of SPB stars are very dense, the observed amplitudes are low (cf. Fig. 4), and most of the currently known SPBs are multi-periodic, giving rise to beat periods of the order of months or even years.

Currently, at least 51 confirmed and 65 candidate galactic SPB stars are known, of which 15 are in open clusters. Thanks to the OGLE-II and MACHO databases, extra-galactic SPBs were recently found: 59 in the LMC and 11 in the SMC (Kołaczkowski et al. 2006). For the SPB stars observed in the Geneva photometric system, the effective temperatures and surface gravities were determined with the code CALIB in the same way as described by De Cat et al. (2007). As shown in Fig. 1, these stars cover the (young) part of the theoretical SPB instability strip. This figure also illustrates the existence of a common part of the theoretical instability strip of the β Cep and SPB stars. At least 6 β Cep/SPB hybrids are currently known: 53 Psc (LeContel et al. 2001), ι Her (Chapellier et al. 2000), ν Eri (Jerzykiewicz et al. 2005), HD 886 (Chapellier et al. 2006), HD 13745, and HD 19374 (De Cat et al. 2007). Since they simultaneously pulsate in low-order p/g modes and high-order g modes probing both the outer layers and the deep interior of these stars, they are ideal asteroseismic targets.

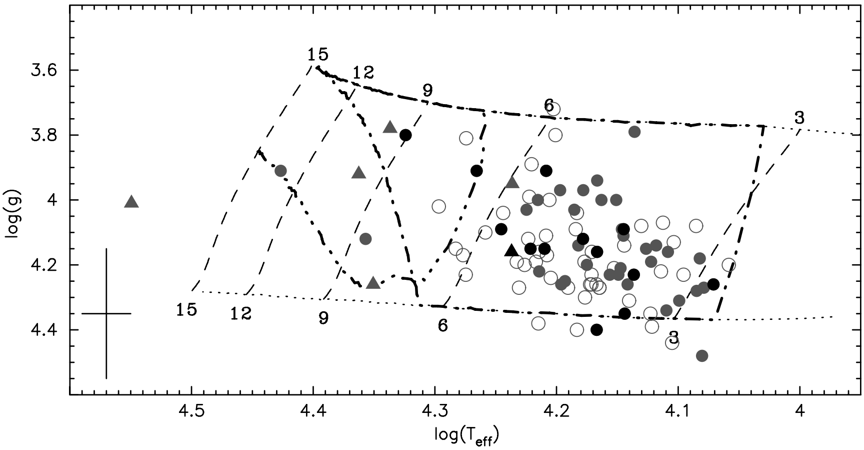

Figure 1: Position in the (log($T_{\rm eff}$),log g)-diagram of the candidate (open symbols) and confirmed (full symbols) SPB stars for which Geneva photometry is available. The triangles indicate the hybrid β Cep/SPB stars. The stars with a detected magnetic field are given in black. The lower and upper dotted lines show the ZAMS and TAMS, respectively. The dashed lines denote evolution tracks for stars with M= 15, 12, 9, 6, and 3 $M_\odot$. The dash-dot-dot-dotted and dash-dotted lines represent the theoretical instability strips for β Cep and SPB modes provided by De Cat et al. (2007). A typical error bar is given in the lower left corner.

Observations

For a successful asteroseismic study, the observation of a large number of well identified modes is mandatory. The detection of frequency multiplets is advantageous. Unfortunately, long-term monitoring with dedicated telescopes has not been enough to provide these basic needs so far. Currently, the best data-sets consist of several hundreds of (mostly) photometric observations spread over some 15 years. Because it concerns single-site data, the frequency analysis suffers from strong aliasing. Moreover, the maximum number of independent frequencies detected with ground-based data, i.e. 8 for HD 160124 (Waelkens 1991), is low. Although there is evidence for frequency multiplets for some stars, the results of the mode identification are still inconclusive for a lot of the observed modes (see below). The organization of (unrealistic) long-term simultaneous photometric and spectroscopic multi-site campaigns is needed to overcome these problems.

Space-based observations can be an alternative solution. Recently, new variable B-stars were discovered thanks to the white-light data obtained in observation campaigns of some 30 consecutive days with the MOST satellite. HD 163830 is a new SPB star for which 20 frequencies below 2 d^{-1} are detected (Fig. 2, left panel). The two lowest frequencies are interpreted as rotation modulation. It has been shown that the remaining frequencies are compatible with unstable ℓ= 1 and/or 2 modes (Aerts et al. 2006). HD 163868 is an SPB emission star for which the 60 observed frequencies below 3.8 d^{-1} are attributed to prograde g modes or to r modes (Walker et al. 2005). HD 163899 is the prototype of a new class of SPB supergiants. The 48 observed frequencies below 2.8 d^{-1} are post-TAMS g modes (Saio et al. 2006). Although MOST already has shown the capability of dedicated space-missions to detect a large number of frequencies, the lack of colour information makes the identification of the modes impossible. Hence, the lack of accurate mode identifications currently prevents us to start asteroseismic modelling for SPB stars.

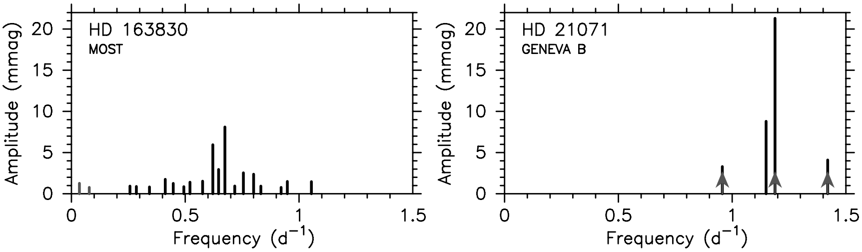

Figure 2: Amplitude spectrum of HD 163830 (left: MOST data; Aerts et al. 2006) and HD 21071 (right: Geneva *B* data; De Cat et al. 2007). The frequencies given in grey are attributed to rotation and those in black to high-order g modes. The spacings between the three observed frequencies of HD 21071 indicated with an arrow are compatible with those expected for a rotationally split $\ell = 1$ mode.

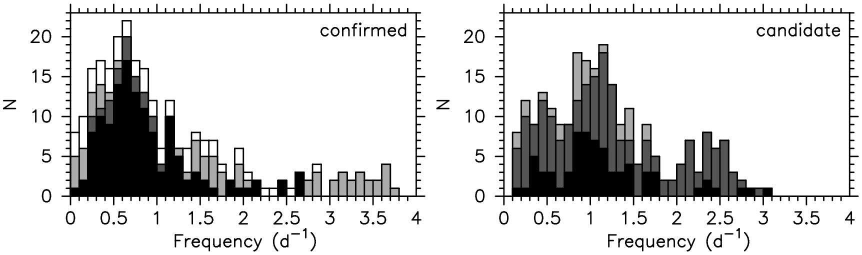

Figure 3: Distributions of the observed SPB frequencies. Left: based on the ground-based observations of confirmed members (black) and on the MOST observations of HD 163830 (dark grey), HD 163868 (light grey), and HD 163899 (white). Right: based on the ground-based observations of the galactic (black) and the extra-galactic (LMC: dark grey; SMC: light grey) candidate members.

Frequencies

The distribution of the observed frequencies of the confirmed and candidate SPB stars are given in the left and right panel of Fig. 3, respectively. For the confirmed SPB stars, the majority of the observed frequencies lies below 1.5 d^{-1}, which is compatible with the frequency range of the theoretically predicted unstable SPB modes (e.g. Dziembowski et al. 1993). The distribution peaks around 0.65 d^{-1} and has a long tail towards higher frequencies. The distribution of the candidate SPB stars is flatter, peaks around 1.10 d^{-1}, and extends up to 3 d^{-1}. It is not clear whether or not the difference in these distributions is significant. Past experience with follow-up observations for a sample of 27 candidate SPB stars selected by Aerts et al. (1999) and Mathias et al. (2001) taught us that we can expect that about 20% of the remaining SPB candidates are misclassified because the SPB-like frequency observed in photometry is due to either binarity or rotational modulation (De Cat et al. 2000, Briquet et al. 2004). High-resolution spectroscopic follow-up data are needed to clarify this issue. In any case, distributions shown for candidate SPB stars should be interpreted with caution.

Amplitudes

The distributions of the observed photometric amplitudes of the confirmed and candidate SPB stars are given in the left and right panels of Fig. 4, respectively. Although it is not obvious to compare the distributions in the different panels because they are based on observations in different photometric filters, it is clear that the observed amplitudes are at maximum a

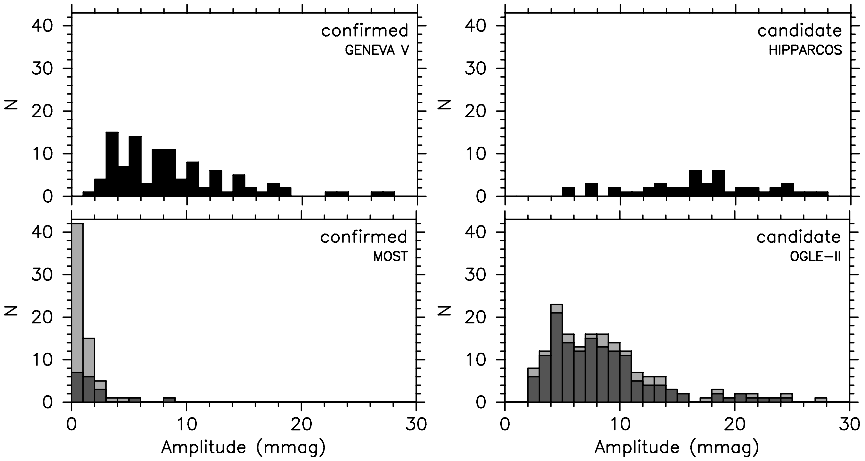

Figure 4: Distributions of the observed SPB amplitudes in photometry. Left: based on the Geneva *V* observations of confirmed members (top) and on the MOST observations of HD 163830 (bottom, dark grey) and HD 163899 (bottom, light grey). Right: based on the Hipparcos H_p observations of candidate galactic members (top) and the OGLE-II observations of candidate members in the LMC (bottom, dark grey) and the SMC (bottom, light grey).

few hundredths of a magnitude. In radial velocity, the amplitudes are below ~10 km s^{-1} (not shown). Also the main difference between ground- and space-based observations is well illustrated: while no modes with amplitudes below ~1 mmag are observed from Earth due to the current detection limits of our ground-based equipment (Fig. 4 top left, top right, and bottom right panels), the MOST observations are dominated by low amplitude modes (Fig. 4 bottom left panel). This indicates that there is a clear need for high-precision observations both to detect and to study the variations of SPB stars in full detail. Hence, space-missions like e.g. CoRoT (launched in December 2006) will provide a gold mine for g-mode research.

Chemical composition

Niemczura (2003) determined the metallicity for a sample of 34 reference and 20 SPB stars based on low-resolution IUE spectra. She found no significant difference between the non-pulsating and pulsating B stars. The average SPB metallicity of $[m/H] \simeq -0.20$ or $Z \simeq 0.013$ was considered as low at the time, but it helped to explain the instability of some of the observed low frequency modes in SPB stars (De Cat et al. 2004). Recently, it became clear that this mean value is close to the "new" solar metallicity (Asplund et al. 2005).

A large project based on high-resolution CORALIE spectra (390–682 nm) with the aim to determine in a self-consistent way the physical parameters ($T_{\rm eff}$ and $\log g$) and the NLTE abundances for the majority of the confirmed SPB stars is ongoing in Leuven. Briquet & Morel (2007) report the first results. For HD 85953, the abundances of the considered chemical elements are, within the errors, indistinguishable from those of OB dwarfs in the solar neighbourhood. For HD 3360, a clear nitrogen excess is found, which is similar to what has been observed for four β Cep stars (Morel et al. 2006). It is too early for general conclusions.

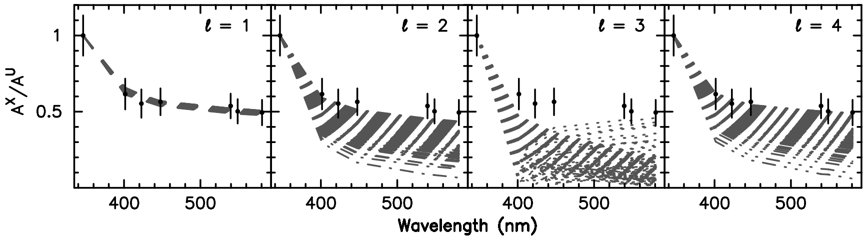

Figure 5: The results of the photometric mode identification for $\nu_1 = 1.1569(6)\ \mathrm{d}^{-1}$ of HD 24587. For each theoretical model within the observed range of $\log(T_{\rm eff})$ and $\log g$ (cf. Fig. 1), the theoretical amplitude ratios for modes with $\ell = 1$, 2, 3, and 4 are represented with a grey dashed, dash-dotted, dotted, and dash-dot-dot-dotted line, respectively, in the panels from left to right. The black dots indicate the observed amplitude ratios and their standard error. The most probable value for ℓ is 1.

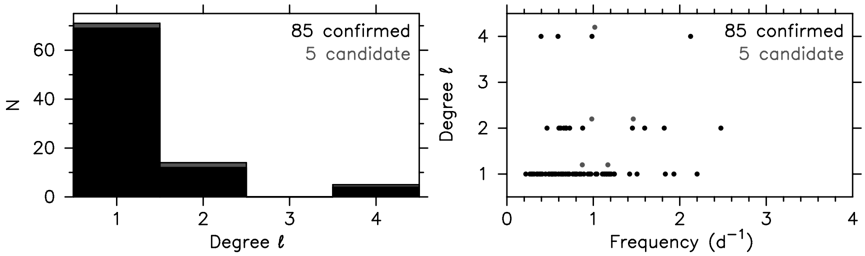

Figure 6: Overview of the most probable values of the spherical degree ℓ for the observed modes of confirmed (black) and candidate (grey) SPB stars with more than 20 observations in the Geneva photometric system. There is a clear dominance of $\ell = 1$ modes (left) and no dependence of ℓ on the observed frequency is found (right).

Mode identification

For the identification of the modes, different techniques can be used. In case multi-colour photometric observations are available, constraints on the spherical degree ℓ can be obtained by comparing observed and theoretical amplitude ratios (e.g., Dupret et al. 2003). For all the observed frequencies of SPB stars with more than 20 observations in the 7 filters of the Geneva photometric system, we applied this method in the same way as De Cat et al. (2007). In this procedure, the modes with eigenfrequencies for $\ell = 1$, 2, 3, and 4 that are the closest to the observed frequency are selected for each model within the observed ($\log(T_{\rm eff})$,$\log g$) error box of a pre-calculated grid of main-sequence models with the "new" solar composition to calculate the theoretical amplitude ratios relative to the Geneva U filter. A representative illustration of the results is given in Fig. 5. For the main frequency of HD 24587, the theoretical amplitude ratios of $\ell = 1$ and 4 modes are compatible with the observed ones. Although the results are inconclusive, $\ell = 1$ is considered as the most probable solution because the relative number of compatible $\ell = 1$ modes is higher. Moreover, $\ell = 4$ modes are less likely to be observed in photometry due to cancellation effects. The global results of the photometric identification exercise are given in Fig. 6. There is a clear dominance of $\ell = 1$ modes (left panel) which is compatible with theoretical expectations (Townsend 2003). No evidence for a dependence of the ℓ value on the observed frequency is found (right panel).

High-resolution spectroscopy can provide constraints on additional parameters including the azimuthal number m, the projected rotational velocity $v \sin i$, and the inclination i. In the moment method, a comparison is made between the first three normalized velocity moments of a time-series of observed line-profiles and theoretical ones computed for a large grid of parameters (Briquet & Aerts 2003). This method performs best in the case of low-degree modes observed in sufficiently slow rotators. Unfortunately, this method generally leads to several equivalent solutions. After calculation of the corresponding time-series of synthetic line-profiles, additional tests may help in selecting the best moment solutions: (1) by comparing phase diagrams of higher order (even) velocity moments derived from the observed and synthetic line-profiles, and (2) by comparing the amplitude and phase variations across the observed and synthetic line-profiles for both the observed frequency and its first harmonic. This identification scheme has already been applied successfully to mono-periodic SPB stars, leading to a unique identification as a prograde dipole mode in four cases (De Cat et al. 2005). The application to multi-periodic SPB stars is ongoing (De Cat et al., in preparation).

Recently, the Fourier parameter fit method has been introduced by Zima (2006) in which the zeropoints, amplitudes and phases across the observed line-profiles for each detected frequency are fitted in a statistically justified way to those derived from synthetic line-profiles. Contrary to the moment method, the best performance is found in the case of higher-degree modes observed in sufficiently rapid rotators. Moreover, it is complementary to the photometric identification because it is able to put severe constraints on m. The first results of its application to multi-periodic SPB stars are presented by Zima et al. (2007).

It is clear that mode identification for g modes is very difficult. The best results are found when both photometric and spectroscopic techniques are simultaneously applied.

Rotation

In Fig. 7, we show the distribution of the projected rotational velocity ($v \sin i$) for the confirmed (left) and candidate (right) SPB stars. It is clear that SPB pulsations are not restricted to slow rotators. For rapid rotators, significant frequency shifts with respect to those in a non-rotating star are expected for non-zonal modes ($m \neq 0$). This argument has already been used to explain the high frequencies observed for e.g. HD 121190: $\nu_1 = 2.6831(4)$ d^{-1}, $\nu_2 = 2.6199(4)$ d^{-1}, and $\nu_3 = 2.4713(7)$ d^{-1} (Aerts & Kolenberg 2005). The corresponding modes have either $\ell = 1$ or 2. The combination of $v \sin i = 118(3)$ km s^{-1} and $R = 1.7(3)$ $R_\odot$ leads to a projected rotational frequency $\Omega \sin i = 1.37(24)$ d^{-1}. In case of retrograde g modes, the frequencies in the co-rotating frame are at least 0.7 d^{-1} lower, which moves them towards the theoretically expected range of unstable modes. This also indicates that the results of mode identification should be treated with caution and that inclusion of rotation in asteroseismic modelling is needed.

We also investigated whether or not the Hipparcos H_p amplitudes depend on rotation. An amplitude drop towards high $v \sin i$ is seen for the confirmed SPB stars (Fig. 7, left panel). Because the slowest rotators were chosen first for follow-up spectroscopic studies, this might be a selection effect. Since rapidly rotating candidate SPB stars with high photometric amplitudes do exist (Fig. 7, right panel), additional observations are needed to confirm or reject them as pulsating stars.

For several stars, close frequency multiplets are observed. In the right panel of Fig. 2, we give the example of HD 21071, for which four frequencies are observed in Geneva data: $\nu_1 = 1.18843(1)$ d^{-1}, $\nu_2 = 1.14934(2)$ d^{-1}, $\nu_3 = 1.41968(7)$ d^{-1}, and $\nu_4 = 0.95706(9)$ d^{-1} (De Cat et al. 2007). The most probable identification is $\ell = 1$ for the four observed modes. It is possible that ν_4, ν_1, and ν_3 (indicated with arrows in Fig. 2) are components of a rotationally split $\ell = 1$ mode because $\Omega \sin i = 0.45(12)$ d^{-1}, which leads to a frequency spacing that is very close to the observed one. Rotational splitting cannot be responsible for the close frequency pair (ν_1, ν_2). Such frequency spacings are compatible with those of modes with either the same degree ℓ but a subsequent radial order n or with different ℓ values.

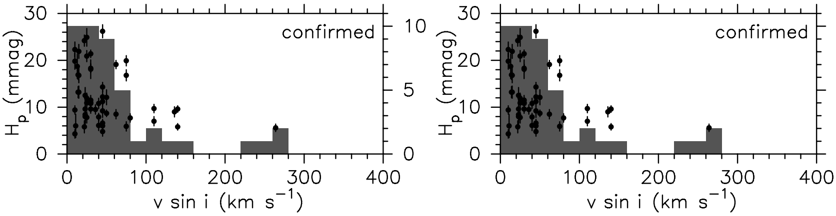

Figure 7: Distribution of the projected rotational velocity ($v \sin i$) for the confirmed (left) and candidate (right) SPB stars. The dots with error bars denote the amplitudes of the observed frequencies in the Hipparcos $H_{\rm p}$ filter.

Magnetic fields

HD 37151 is the first SPB star for which four magnetic field measurements were carried out (Borra 1981), but the results were compatible with a zero field (North & Paltani 1994). HD 3360 is an SPB star with a rotational period $P_\Omega = 5.37$ d and a pulsation frequency of $0.64\ \mathrm{d}^{-1}$ for which Neiner et al. (2003) detected a polar magnetic field of $B_{\rm pol} = 335^{+120}_{-65}$ G. Its longitudinal component varies sinusoidally with P_Ω. In the case of a simple dipolar configuration, a polar field of 120 G on the surface corresponds to a polar field of 110 kG in the vicinity of the convective core, which causes a frequency splitting of 1% for a g^1_{20}-mode (Hasan et al. 2005). Hence, magnetic fields are a valuable alternative explanation for the very close frequency multiplets observed in several SPB stars since longitudinal magnetic fields of a few hundred G have been detected recently in another thirteen SPB stars (Hubrig et al. 2006). The SPB stars with a confirmed magnetic field are given in black in Fig. 1. The inclusion of magnetic fields in theoretical models is needed because it concerns a significant fraction of the known members. From a comparative study between pulsating SPB stars and non-pulsating Bp stars, Briquet et al. (2007) conclude that the group of SPB stars is younger and has a weaker longitudinal magnetic field than the group of Bp stars.

Conclusions

The potential of seismology of SPB stars is excellent, and the potential of β Cep/SPB hybrids is even better since they probe both the deep stellar interior and the outer layers. Before we can move on to in-depth asteroseismic modelling of SPB stars, we need (1) long-term multi-site and/or space-based data, (2) accurate mode identification techniques for g modes, and (3) the inclusion of magnetic fields and rotation in the theoretical models.

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DISCUSSION

Handler: As Mike Breger has pointed out in his talk, there are some fundamental limits to frequency analysis. One of them is the resolution of the data set, so you can only resolve frequencies to $1.5/T$. If you look at the frequencies of the MOST data for some of these B stars, about two thirds of them are not resolved. So I would like to discourage theorists to model individual frequencies of these stars; frequency ranges are still OK. The other thing that worries me is that MOST observes about 30 cycles of the variations of those stars and then finds about 60 frequencies in these data, which is also a little incredible in my view.

Dziembowski [to Handler]: It is very difficult to discourage theorists from interpreting data that are so interesting. *[To De Cat:]* Would you say that the current data are consistent with the hypothesis that all B-type stars in the proper range of the HR diagram are pulsating?

De Cat: I can't say because the higher the precision, the lower amplitudes you can find.

Dziembowski: But is the trend consistent with the idea that pulsation in this part of the HR diagram is a universal phenomenon?

De Cat: I think so, but I can't be sure.