

## PULSATONAL ANALYSIS OF V 588 MON AND V 589 MON OBSERVED WITH THE *MOST*\* AND *CoRoT*† SATELLITES

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### ABSTRACT

The two pulsating pre-main sequence (PMS) stars V 588 Mon and V 589 Mon were observed by *CoRoT* for 23.4 days in 2008 March during the Short Run SRa01 and in 2004 and 2006 by *MOST* for a total of  $\sim 70$  days. We present their photometric variability up to  $1000 \mu\text{Hz}$  and down to residual amplitude noise levels of 23 and 10 ppm of the *CoRoT* data for V 588 Mon and V 589 Mon, respectively. The *CoRoT* imagerie data as well as the two *MOST* data sets allowed for detailed frequency analyses using Period04 and SigSpec. We confirm all previously identified frequencies, improve the known pulsation spectra to a total of 21 frequencies for V 588 Mon and 37 for V 589 Mon, and compare them to our PMS model predictions. No model oscillation spectrum with  $l = 0, 1, 2$ , and 3  $p$ -modes matches all the observed frequencies. When rotation is included we find that the rotationally split modes of the slower rotating star, V 589 Mon, are addressable via perturbative methods while for the more rapidly rotating star, V 588 Mon, they are not and, consequently, will require more sophisticated modeling. The high precision of the *CoRoT* data allowed us to investigate the large density of frequencies found in the region from 0 to  $300 \mu\text{Hz}$ . The presence of granulation appears to be a more attractive explanation than the excitation of high-degree modes. Granulation was modeled with a superposition of white noise, a sum of Lorentzian-like functions, and a Gaussian. Our analysis clearly illustrates the need for a more sophisticated granulation model.

*Key words:* asteroseismology – stars: individual (V 588 Mon, V 589 Mon) – stars: pre-main sequence – stars: variables: delta Scuti – techniques: photometric

*Online-only material:* color figures

### 1. INTRODUCTION

V 588 Mon (HD 261331, NGC 2264 2) and V 589 Mon (HD 261446, NGC 2264 20) are two pre-main sequence (PMS) pulsating stars for which there exists strong evidence that they are the members of the young open cluster NGC 2264. The proper motions for both stars are in agreement with the clusters average proper motion (Hog et al. 2000) and both fit the clusters Hertzsprung–Russell (HR) and color–magnitude diagrams well. A radial velocity measurement only exists for V 589 Mon (Strom et al. 1971), but it is consistent with the values for other cluster members. Finally, the radial velocities of emission lines in the optical spectra of the two stars caused by interstellar gas match the radial velocities of the cluster, suggesting that both stars are indeed embedded in gas clouds belonging to the cluster (Kallinger et al. 2008b).

The cluster has a diameter of  $\sim 39$  arcmin and belongs to the Mon OB 1 association. The age of NGC 2264 is reported in the literature to lie between three (e.g., Walker 1956; Sung et al. 2004) and 10 million years (e.g., Sagar et al. 1986). With such a young age, the cluster's main sequence only consists of massive

O- and B-type stars, while stars of later spectral types are still in their PMS phase. Therefore, V 588 Mon and V 589 Mon having spectral types of A7 and F2, respectively, have not yet arrived on the zero-age main sequence (ZAMS).

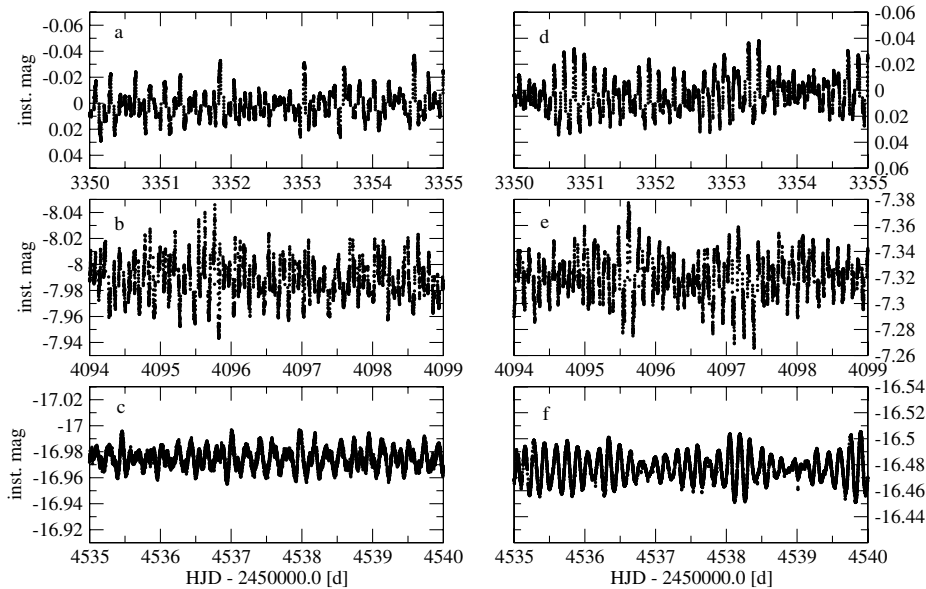
The  $\delta$  Scuti-like variability of V 588 Mon and V 589 Mon was first reported by Breger (1972). Hence, they were the first pulsating PMS stars discovered. In the meantime, the number of known  $\delta$  Scuti-like PMS pulsators has increased from 36 (Zwintz 2008) to  $\sim 60$  (K. Zwintz 2011, private communication) due to dedicated observations from ground and from space.

Pulsating PMS stars have intermediate masses, i.e., between  $\sim 1.5$  and  $4 M_{\odot}$  and can become vibrationally unstable when they cross the instability region in the HR diagram on their way to the ZAMS. Pre- and post-main sequence evolutionary tracks for the same stellar mass intersect several times close to the ZAMS which makes the determination of the evolutionary stage of a field star from only its effective temperature, luminosity, and mass ambiguous. Additional information such as typical observational evidence for the PMS evolutionary stage (i.e., emission lines, IR excess, an X-ray flux, located in an obscured region on the sky etc.) or membership to very young open clusters is needed to resolve this ambiguity. Another way to distinguish the evolutionary stages can come from the asteroseismic interpretation of the observed pulsation frequencies (Guenther et al. 2007).

Time series photometry for V 588 Mon and V 589 Mon has been obtained from a multi-site ground-based campaign

\* Based on data from the *MOST* satellite, a Canadian Space Agency mission, jointly operated by Dynacon Inc., the University of Toronto Institute for Aerospace Studies, and the University of British Columbia with the assistance of the University of Vienna.

† The *CoRoT* space mission, launched on 2006 December 27, has been developed and is operated by CNES, with the contribution of Austria, Belgium, Brazil, ESA (RSSD and Science Programme), Germany, and Spain.



**Figure 1.** Five-day subsets of the *MOST* 2004 (a,d), *MOST* 2006 (b,e), and *CoRoT* (c,f) light curves for V 588 Mon (left) and V 589 Mon (right) to the same y-axis scale. The different amplitudes in the *MOST* vs. the *CoRoT* light curves are mainly due to the different bandpasses used in the two satellites.

(Kallinger et al. 2008b) and from two observing runs of the Canadian *Microvariability and Oscillations of STars* (*MOST*) space telescope (Walker et al. 2003) in 2004 and 2006 (Guenther et al. 2009). The eight and 12 frequencies common to these three data sets for V 588 Mon and V 589 Mon, respectively, were submitted to a first asteroseismic analysis (Guenther et al. 2009). The accuracy of the *MOST* observations is higher than that of the ground-based data. Hence, it is not surprising that the two *MOST* data sets yield more significant frequencies at lower amplitudes that were not found in the ground-based observations. The *CoRoT* (Convection, Rotation, and planetary Transits) observations of the two PMS pulsators are new and independent data sets of unprecedented accuracy that allow us for the first time to investigate other effects (e.g., granulation) in PMS stars. As both *MOST* data sets and the *CoRoT* data are available to us, we use them together for a detailed pulsational analysis.

## 2. OBSERVATIONS AND DATA REDUCTION

### 2.1. *MOST* Observations

The *MOST* space telescope (Walker et al. 2003) was launched on 2003 June 30 into a polar Sun-synchronous circular orbit with an orbital period of  $\sim 101$  minutes (corresponding to an orbital frequency of  $14.2 \text{ d}^{-1}$ ). From its orbital vantage point, *MOST* can obtain uninterrupted observations of stars located in its Continuous Viewing Zone for up to eight weeks. The *MOST* satellite houses a 15 cm Rumak–Maksutov telescope, feeding a CCD photometer through a single, custom broadband optical filter (covering wavelengths from 350 to 750 nm).

The *MOST* can supply up to three types of photometric data simultaneously for multiple targets in its field. The mission was originally intended only for Fabry Imaging, in which an image of the entrance pupil of the telescope—illuminated by a bright target star ( $V < 6$ )—is projected onto the instrument’s Science CCD by a Fabry microlens (see Reegen et al. 2006) for details. After *MOST* was operating in orbit, the pointing performance of the satellite was improved so much that a new mode of observing, Direct Imaging, was made practical. Direct

Imaging is much like conventional CCD photometry, in which photometry is obtained from defocused images of stars in the open area of the CCD not covered by the Fabry microlens array field stop mask. In the original design, no scientific information was available from the Guide Stars used for the Attitude Control System, but now precise photometry is possible for these stars as well (see, e.g., Walker et al. 2005; Aerts et al. 2006).

V 588 Mon and V 589 Mon were observed in the direct imaging mode, first from 2004 December 6 to 2005 January 24 and second within the NGC 2264 observations (see Zwintz et al. 2009) from 2006 December 7 to 2007 January 4. The light curves have therefore time bases of 48.13 days in 2004 and 22.77 days in 2006. In 2004, on-board exposures were 15 s long sampled twice per minute. A five-day subset light curve of V 588 Mon from 2004 is shown in panel a of Figure 1, and the respective V 589 Mon five-day subset light curve is shown in panel d. The 2006 data had exposure times of 1.5 s; 16 consecutive images were added on top of each other and the sampling time was 24 s (Zwintz et al. 2009). Five-day subsets of the light curves for V 588 Mon and V 589 Mon from the 2006 data are given in panels b and e of Figure 1, respectively.

Data reduction of the *MOST* direct imaging photometry was conducted using the method developed by Rowe et al. (2006) which combines classical aperture photometry and point-spread function fitting to the direct imaging subasters.

### 2.2. *CoRoT* Observations

The *CoRoT* satellite (Baglin 2006) was launched on 2006 December 27, from Baikonur aboard a Soyuz rocket into a polar, inertial circular orbit at an altitude of 896 km. With its 27 cm telescope, *CoRoT* can observe stars within a field of view of about  $1.3 \times 2.6 \text{ deg}^2$  located inside two cones of  $10^\circ$  radius, one at a right ascension of 06:50 (galactic anticenter direction) and another at 18:50 (galactic center direction).

The *CoRoT* space telescope originally had two CCDs devoted to asteroseismology for stars with  $5.7 < m_V < 9.5$  mag and two CCDs dedicated to the search for exoplanets where  $\sim 6000$  stars in the magnitude range from 10 to 16 mag in  $R$  per CCD are monitored. Observations of the young open cluster NGC 2264

were conducted as dedicated Short Run, SRa01, uninterrupted for 23.4 days in 2008 March within the framework of the *Additional Programme* (AP; Weiss 2006). At the middle of SRa01, the ascending mode of the orbital plane was 15°67. The complete cluster was placed in one of the two Exofield CCDs and data were taken for all stars in the accessible magnitude range. The 100 observed brightest stars in the field of the cluster were primary targets to search for stellar pulsations in PMS stars. A detailed description will be given in K. Zwintz et al. (2011, in preparation).

With  $V = 9.7$  mag and  $V = 10.3$  mag, V 588 Mon and V 589 Mon are nominally too bright to be observed in the *CoRoT* Exofield. Obtaining data for these two stars was only possible using the method of the so-called *CoRoT* imagettes.

Per observing run up to 20 imagettes,  $15 \times 10$  pixel large CCD subwindows, can be defined in each of the two *CoRoT* Exofield CCDs. SRa01 was the first *CoRoT* observing run, for which the imagette data were requested for scientific use and allowed to observe stars that normally would be too bright for the Exofield. Each of the imagettes is submitted to a special data reduction pipeline developed by the Laboratoire d'Astronomie de Marseille and the Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique. The reduction includes the flagging of data obtained during passes of the satellite through the South Atlantic Anomaly (SAA), the calculation of a photometric mask, the detection of cosmic, contaminants, outliers due to the satellite jitter and hot pixels, and filtering of the orbital signal. A detailed description will be given in M. Auvergne et al. (2011, in preparation).

In preparation for the NGC 2264 observations, a prioritized target catalog consisting only of the stars brighter than the Exofield-CCD magnitude limit was generated. From the 20 possible windows on the Exofield CCD1, 14 were used to observe some of the previously selected objects including the two known PMS pulsators V 588 Mon and V 589 Mon. Figure 1 shows five-day subsets of the respective light curves (panels c and f). Note that the different filter bandwidths of the *CoRoT* (from 370 to 1000 nm) compared to the *MOST* (from 350 to 750 nm) data are caused by the different passbands used in the two satellites.

### 2.3. Frequency Analysis

Frequency analyses were conducted using Period04 (Lenz & Breger 2005) which combines Fourier and least-squares algorithms. Frequencies are prewhitened subsequently and are considered to be significant if their amplitudes exceed four times the local noise level in the amplitude spectrum (Breger et al. 1993; Kuschnig et al. 1997).

For the *MOST* data sets, the formally significant frequencies were checked against the instrumental frequencies related to the orbit of the satellite, its harmonics and one  $d^{-1}$  sidelobes within the frequency resolution (computed according to Kallinger et al. 2008a). In the *CoRoT* data, the influence of the satellite's orbital and related frequencies is negligible.

## 3. PULSATION AND GRANULATION OF V 588 MON AND V 589 MON

### 3.1. Modeling the Stellar Background in the *CoRoT* Data

Assuming white, i.e., frequency-independent, background noise, the 23.4 days long *CoRoT* time series for V 588 Mon

and V 589 Mon showed 106 and 197 formally significant frequencies, respectively, after the initial frequency analysis with the methods described above. Although the numbers of frequencies are lower than the many hundreds of frequencies reported for classical Scuti stars observed by *CoRoT* (e.g., Poretti et al. 2009, observed  $> 1000$  frequencies in HD 50844), they are still too many to be accounted for as simply individually excited low  $l$ -valued  $p$ -modes. Asteroseismic models predict some tens of  $p$ -modes with degrees  $l < 4$ , which are potentially excited in the frequency range of  $\delta$  Scuti-type oscillations. A substantially larger number of modes would have to include modes of degree  $l > 4$  and/or rotationally split modes and/or the possibility that the detected modes are part of the intrinsic background noise due to granulation.

If all  $l$ -valued  $p$ -modes are driven to similar amplitudes, then the geometric cancellation effect reduces the observable amplitude by more than an order of magnitude for  $l > 3$   $p$ -modes (see, for example, the spatial response functions in Christensen-Dalsgaard & Gough 1982). But Daszynska-Daszkiewicz et al. (2006) note that some stars exhibit more than two orders of magnitude variations in pulsation amplitudes. In addition, when observing in luminosity the geometric cancellation effect is offset by an  $l^2$  factor. Regardless, the variation in amplitude of the modes in the Short Run data (23 days) from *CoRoT* and in the *MOST* data is a little more than one order of magnitude. We are not yet reaching the lower amplitude modes, for which these effects become important. Furthermore, we note that unlike the example of HD 50844 observed by Poretti et al. (2009) we do have data for V 588 Mon and V 589 Mon from different instruments obtained at different epochs. If all the frequencies were due to pulsation modes, then they (or at least the majority) should appear in all data sets. However, apart from the frequencies listed in Tables 2 and 3, we find five to 10 frequencies that coincide (within the frequency uncertainties) in the *CoRoT* and *MOST* data sets for both stars. The number depends on the considered frequency range, the chosen significance limits, and how the coincidence and frequency error is defined in detail. But even for two totally unrelated data sets it would not be surprising to find a few coincident frequencies. In the case of V 588 Mon, for example, most of the 106 formally significant frequencies in the *CoRoT* data are distributed between about five and  $15 d^{-1}$  in about 700 independent frequency bins. The frequency bin size is one over the data set length times the square root of the significance (Kallinger et al. 2008a). For our analysis we use an average significance of 10. Even if the formally significant frequencies in the *CoRoT* data set were just random numbers, one could expect to find by chance matches for at least a few of them with the 179 formally significant frequencies determined from the *MOST* data. Hence, at this time, we argue that many of the low-amplitude frequencies in the *CoRoT* data are due to granulation and a (rare) coincidence with low-amplitude *MOST* frequencies is not indicative for pulsation.

Kallinger & Matthews (2010) concluded that many of the low-amplitude frequencies in  $\delta$  Scuti stars are consistent with a strongly frequency-dependent intrinsic background signal due to granulation or some effect similar to granulation. This is well known for cool stars with convective envelopes. The turbulent motions in their outer convective envelopes generate quasi-stochastic power, with amplitudes strongly decreasing for shorter time scales. Although the signal is quasi-stochastic in the time domain, its Fourier transform is Lorentzian-like, where different physical processes on (or near) the stellar surface produce the same type of signal but on different amplitude and



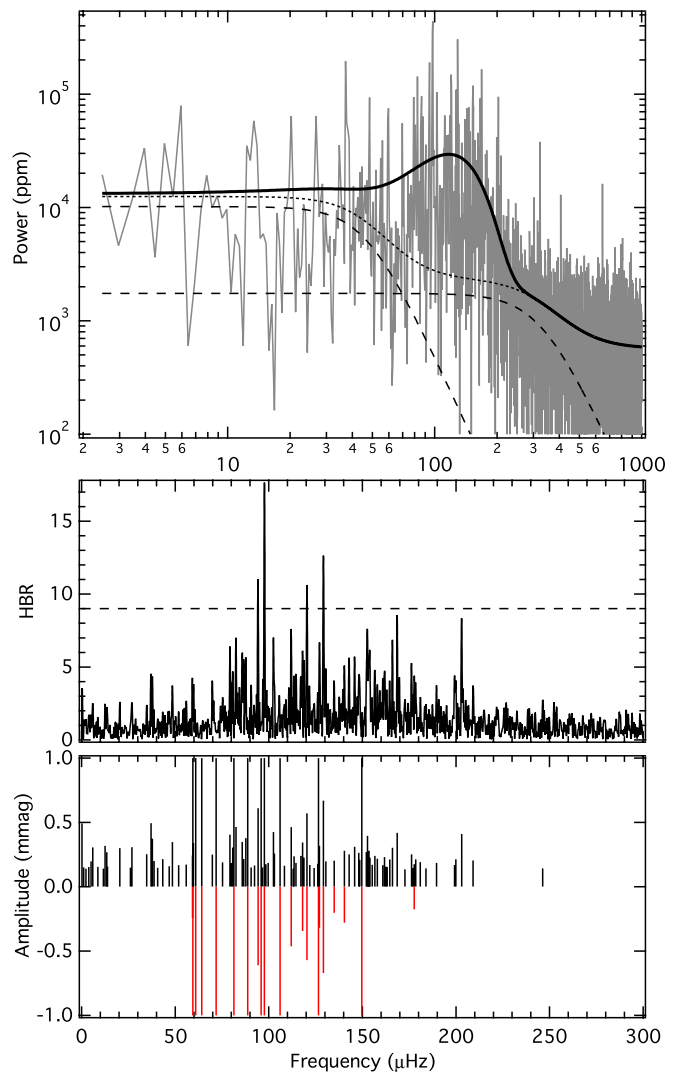
timescales. For the Sun and other Sun-like stars, the different signal components are usually assigned to stellar activity, activity of the photospheric/chromospheric magnetic network, and granulation, with timescales ranging from months for active regions to minutes for granulation (see, e.g., Michel et al. 2008, 2009).

The presence of a granulation background signal depends, of course, on the presence of a surface convection zone, which is usually attributed to stars cooler than the red border of the classical instability strip. On the other hand, it is known that stellar evolutionary models for stars in the instability strip predict a thin convective surface layer and they should therefore show a similar signature of granulation as cool stars in their power spectra. We believe that this was not only recognized before in classical  $\delta$  Scuti stars, but also in PMS  $\delta$  Scuti stars because the amplitudes are small and a clear detection requires long and uninterrupted observations to achieve a high-frequency instrumental noise well below 100 ppm, which have become available only recently. Although the *MOST* observations of V 588 and V 589 Mon are of unprecedented length and completeness, the granulation signal with a low-frequency amplitude of roughly 100 ppm (see Figures 2 and 3) is hidden in the instrumental noise (see Table 1). Only the *CoRoT* observations are sufficient to reveal the strongly frequency-dependent background signal.

### 3.1.1. V 588 Mon

The *CoRoT* light curve of V 588 Mon consists of 56978 data points sampled with 32 s and has a noise level of 47 ppm in the original amplitude spectrum from 0 to  $100 \text{ d}^{-1}$  (see Table 1). The first frequency analysis resulted in 106 formally significant frequencies with signal-to-noise (S/N) values larger than four. Among those are also the previously published eight pulsation frequencies (Guenther et al. 2009).

A visual inspection of the power spectrum of V 588 Mon reveals that the average power per frequency bin (e.g.,  $10 \mu\text{Hz}$ ) is roughly constant at low frequencies and drops by more than one magnitude beyond about  $500 \mu\text{Hz}$ , which is a clear indication for a frequency-dependent noise. To model the background signal, the pulsation power has to be taken into account as well. This is relatively straightforward for cool stars, where the envelope of the pulsation power excess is well approximated by a Gaussian. This is more complicated for stars in the instability strip where the excess envelope can be quite different from a Gaussian (or any other simple function). We follow the approach of Kallinger & Matthews (2010) and first prewhiten the 10 frequencies with the most significant peaks (i.e., the highest amplitudes) and assume the residual pulsation power excess to be at least Gaussian-like. Although NGC 2264 was observed continuously for the 23.4 days, several data points were removed during the reduction process mostly due to high-energy particle hits during the satellites passes through the SAA leading to regular gaps in the time series. The resulting alias peaks would significantly distort a fit to the power spectrum. We therefore filled the gaps—but only for the time series used to investigate the background characteristics which requires uninterrupted data—with linearly interpolated values to receive the needed clean window function. The power spectrum of the gap-filled data is shown in Figure 2. The residual power spectrum is modeled with a superposition of white noise, two Lorentzian-like functions, and a Gaussian. The resulting global fit (solid line in Figure 2) reproduces the overall shape of the residual power spectrum and demonstrates the strong frequency dependence of



**Figure 2.** Top panel: residual gap-filled power spectrum of V 588 Mon (gray) after prewhitening the 10 highest amplitude frequencies. The global fit is shown as solid line, while the dotted line illustrates the model without the pulsational components consisting of the two Lorentzian-like functions and white noise, and the dashed lines mark the two Lorentzian-like functions. Middle panel: residual power spectra normalized to the background components, where the dashed line marks a HBR of nine (given in power). Bottom panel: comparison between the 106 formally significant frequencies (positive values) and the identified 21 pulsation frequencies (negative values) which consist of the 10 prewhitened peaks before granulation modeling, four peaks exceeding an HBR value of nine and seven peaks common to all available data sets.

(A color version of this figure is available in the online journal.)

the background signal. The residual power spectrum is then corrected for the background signal by using the global fit without the pulsation component. Finally, we use the height-to-background ratio (HBR; middle panel of Figure 2) to rate the significance of the individual frequencies received from the initial frequency analysis and consider only frequencies that exceed an HBR value of nine to originate from pulsation. For V 588 Mon four frequencies match this criterion (see Table 2 and Figure 2). Together with the 10 prewhitened frequencies of highest amplitudes, a total of 14 pulsation frequencies remain after granulation modeling. There are a number of peaks in the middle panel of Figure 2 between about  $70$  and  $200 \mu\text{Hz}$  that have a higher HBR value than the peaks in the surrounding frequency ranges but which do not exceed our formal limit of

**Table 1**

Properties of the V 588 Mon and V 589 Mon Data Sets Obtained from *MOST* in 2004 and 2006 and from *CoRoT* in 2008: Time Base (T), Frequency Resolution (Fres), Number of Data Points (*N*), Point-to-point Scatter (pt2pt), Standard Deviation ( $\sigma$ ), and Noise Level Computed from the Original Data Sets from 0 to 100  $\text{d}^{-1}$  (Noise Level)

Data Set	Star	T (d)	Fres ( $\text{d}^{-1}$ )	<i>N</i> (No.)	pt2pt (mag)	$\sigma$ (mag)	Noise Level (ppm)
<i>MOST</i> 04	V 588 Mon	48.13	0.02	59344	0.008	0.015	125
	V 589 Mon	48.13	0.02	60386	0.009	0.018	133
<i>MOST</i> 06	V 588 Mon	22.77	0.04	23137	0.013	0.022	405
	V 589 Mon	22.77	0.04	23113	0.013	0.024	429
<i>CoRoT</i>	V 588 Mon	23.41	0.04	56978	0.003	0.007	47
	V 589 Mon	23.41	0.04	57092	0.0009	0.010	61

$\text{HBR} \geq 9$ . This indicates that there are additional pulsation frequencies, but our simplistic model of the pulsation power excess underestimates their significance.

### 3.1.2. V 589 Mon

The *CoRoT* light curve of V 589 Mon has 57092 data points also obtained with an exposure time of 32 s and the noise level in the amplitude spectrum of the original data set is 61 ppm from 0 to 100  $\text{d}^{-1}$  (Table 1). After the initial frequency analysis, 197 frequencies were identified to be formally significant. Similar as for V 588 Mon, all previously published 12 pulsation frequencies (Guenther et al. 2009) were also detected in the *CoRoT* data.

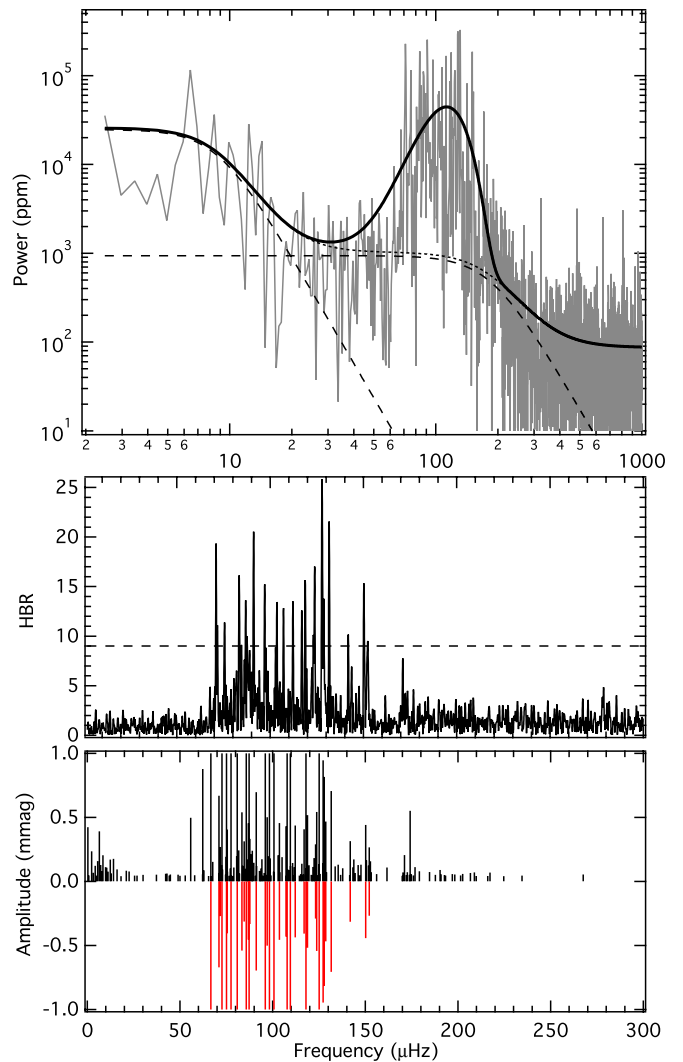
The same method as described for V 588 Mon was used for V 589 Mon. In this case, the 15 frequencies with the highest amplitudes were prewhitened before the gaps in the residuals were filled by linear interpolation (Table 3). The top panel of Figure 3 shows the power spectrum of the gap-filled data (gray), the global model fit (solid line), the model without the pulsational component (dotted line), and the two Lorentzian-like functions (dashed lines). Twenty-two frequencies show an HBR value larger than nine in power (middle panel in Figure 3). Together with the 15 frequencies of highest amplitudes that were prewhitened, a total of 37 frequencies are attributed to be caused by pulsation (see Figure 5 and Table 3).

### 3.2. Comparison of the *MOST* 2004 and 2006 Data to the *CoRoT* Data

The *MOST* 2004 light curves of V 588 Mon and V 589 Mon have 59344 and 60386 data points, respectively. The noise levels in the original amplitude spectra computed from 0 to 100  $\text{d}^{-1}$  (i.e., 0 to 1157  $\mu\text{Hz}$ ) are 125 and 133 ppm (see Table 1). In 2006, V 588 Mon and V 589 Mon were observed only less than half the time as for 2004; hence, the light curves consist only of 23137 and 23113 data points, respectively, and the resulting noise levels from 0 to 100  $\text{d}^{-1}$  in the original amplitude spectra are 405 and 429 ppm (Table 1).

For each star, a separate frequency analysis was conducted and the frequencies common to both data sets were then used for the further analysis and for comparison to the *CoRoT* data. The modeling of the background noise was not possible due to the lower quality of the *MOST* data compared to the *CoRoT* observations.

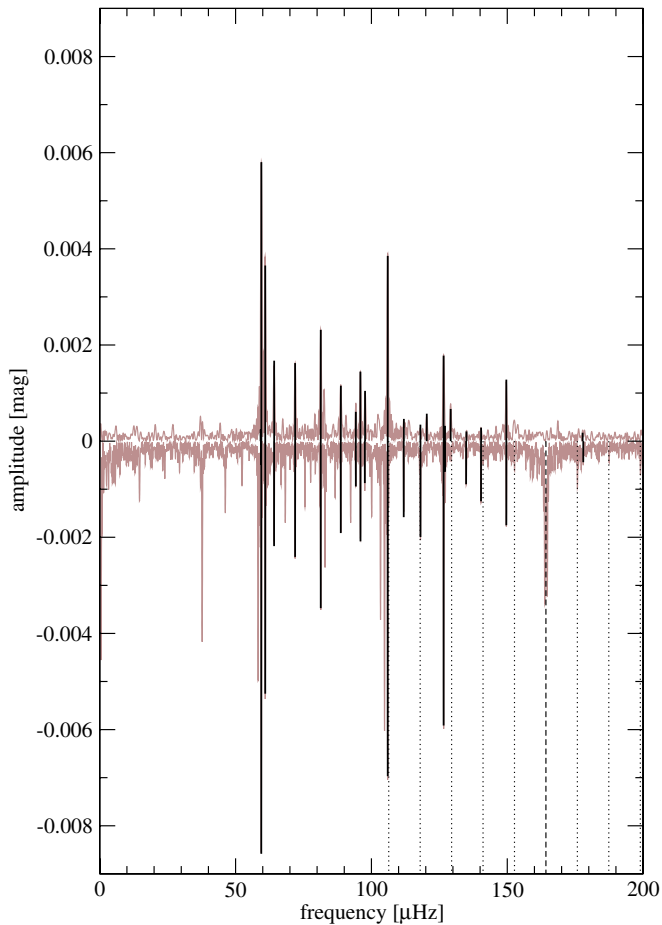
For V 588 Mon, 20 significant frequencies are common to the *MOST* data sets of 2004 and 2006. A cross identification with the 14 *CoRoT* frequencies that remain after granulation modeling showed that 12 of them are also present in the *MOST*



**Figure 3.** Top panel: residual gap-filled power spectrum of V 589 Mon (gray) after prewhitening the 15 highest amplitude frequencies. The global fit is shown as solid line, while the dotted line illustrates the models without the pulsational component consisting of the two Lorentzian-like functions (dashed lines) and white noise, and the dashed lines mark the two Lorentzian-like functions. Middle panel: residual power spectra normalized to the background components, where the dashed line marks a HBR of nine (given in power). Bottom panel: comparison between the 197 formally significant frequencies (positive values) and the identified 37 pulsation frequencies (negative values) which consist of the 15 prewhitened peaks before granulation modeling and the 12 additional peaks exceeding an HBR value of nine.

(A color version of this figure is available in the online journal.)

data (Table 2). A further cross-check of the formally significant *CoRoT* frequencies before the background noise modeling to the 20 frequencies appearing in the *MOST* 2004 and 2006 data resulted in seven additional common frequencies (F15–F21 in Table 2). Although these peaks have HBR values lower than nine, and hence would be attributed to be caused by background noise, they have to be considered as pulsational. Such stable frequencies that are present in three independent data sets obtained in three different years are unlikely to be caused by granulation. Additionally, the shape of the pulsational power excess is very likely more complicated than a Gaussian that is used in the power spectrum model (Kallinger & Matthews 2010) and in the future a more realistic approach will be needed. Therefore, for V 588 Mon, 19 pulsation frequencies are in



**Figure 4.** Comparison of the V 588 Mon amplitude spectra (gray) derived from *CoRoT* (oriented upward) and *MOST* 2004 (negative values assigned) data where the respective 21 and 19 pulsation frequencies are identified in black; the dashed line marks the *MOST* orbital frequency and the dotted lines are the respective  $1 \text{ d}^{-1}$  sidelobes.

(A color version of this figure is available in the online journal.)

common between the *MOST* 2004, *MOST* 2006, and *CoRoT* data sets (Table 2) and are marked as black lines in the bottom panel of Figure 4. A comparison between the 106 formally significant frequencies and the identified 21 pulsation frequencies for V 588 Mon is given in the bottom panel of Figure 2 and illustrates the influence of granulation to the frequency spectrum.

For V 589 Mon, 19 significant frequencies are common to the *MOST* data sets of both years. Seventeen of those were also identified in the *CoRoT* data after granulation modeling and are marked as black lines in the bottom panel of Figure 5. The two additional frequencies appearing in the *MOST* data were identified likely to be aliases or caused by instrumental effects. The comparison between the formally significant 197 frequencies and the identified 37 pulsational peaks is shown in the bottom panel of Figure 3.

Using both *MOST* data sets and the *CoRoT* data, in total 21 pulsation frequencies are identified for V 588 Mon (black lines in the top panel of Figure 4) and 37 for V 589 Mon (black lines in the top panel of Figure 5) where two and 20 of them, respectively, are unique discoveries obtained with *CoRoT*. All *MOST* frequencies have a counterpart in the *CoRoT* observations.

**Table 2**

V 588 Mon: 21 Pulsation Frequencies (Freq) Identified from the *CoRoT* Data with Their Respective Last Digit Errors Given in Parentheses, Amplitudes (amp), HBR Where Appropriate, Flag for Frequencies Also Present in the *MOST* 2004 and 2006 Data Sets (*MOST*), and the Cross-identification to the Previously Published 8 Frequencies (Gue09; Guenther et al. 2009)

No.	Frequency ( $\text{d}^{-1}$ )	Frequency ( $\mu\text{Hz}$ )	amp (mmag)	HBR Power	<i>MOST</i> y / n	Gue09 No.
F1	5.1394(7)	59.484(8)	5.804		y	F1
F2	9.1579(9)	105.99(1)	3.853		y	...
F3	5.2628(8)	60.91(1)	3.653		y	F3
F4	7.029(1)	81.35(1)	2.315		y	F4
F5	10.935(1)	126.56(2)	1.779		y	F2
F6	5.546(1)	64.19(2)	1.673		y	F5
F7	6.213(1)	71.91(2)	1.624		y	...
F8	8.290(2)	95.95(2)	1.446		y	F6
F9	12.930(2)	149.65(2)	1.279		y	...
F10	7.668(2)	88.74(2)	1.152		y	F7
F11	8.438(2)	97.67(2)	1.046	17.6	y	...
F12	11.161(3)	129.18(4)	0.670	12.6	n	...
F13	8.145(3)	94.27(4)	0.610	11.0	y	...
F14	10.400(4)	120.37(4)	0.571	10.6	n	...
F15	9.672(4)	111.95(5)	0.464	7.6	y	...
F16	10.198(6)	118.03(7)	0.344	6.1	y	...
F17	10.981(6)	127.10(7)	0.317	6.7	y	F8
F18	12.128(7)	140.37(8)	0.280	5.1	y	...
F19	5.115(8)	59.20(9)	0.243	4.3	y	...
F20	11.661(9)	134.9(1)	0.203	4.1	y	...
F21	15.36(1)	177.7(1)	0.175	4.4	y	...

**Notes.** The first 10 frequencies with the respective highest amplitudes were prewhitened before granulation modeling.

#### 4. ASTEROSEISMIC ANALYSIS OF V 588 MON AND V 589 MON

For any seismic modeling of a star to be successful it is critical that the identified frequencies are, in fact,  $p$ -modes (or  $g$ -modes) intrinsic to the star. Errant or spurious frequencies are difficult to isolate by modeling alone. Because viable models are based on a large parameter space, many possible solutions for various combinations and selections of the observed frequencies can be produced. In specific terms, when, as is often the case, it is impossible to find a model fit to all the observed frequencies, there usually exist multiple possibilities of fitting some subset of the observed frequencies and no decisive way to prefer one solution over the others.

*CoRoT* observations of both V 588 Mon and V 589 Mon have yielded a large number of frequencies, many of which were also seen by *MOST* (Guenther et al. 2009). The two independent observations go a long way toward confirming the intrinsic, i.e., non-instrumental, nature of the frequencies. Furthermore, since the *MOST* and *CoRoT* observations are separated in time by several years, they imply that the modes are stable over a period of at least four years.

Both stars show significant  $v \cdot \sin i$  velocities, high enough, to produce resolvable splittings in the frequency domain. Unfortunately, the mode identification is complicated by the fact that the predicted splitting frequencies are comparable to the characteristic (i.e., asymptotic large) spacing that separates  $p$ -mode frequencies, thereby, making it difficult to distinguish the split sidelobes from the parent frequencies. Furthermore, if the stars are rapidly rotating, then the splittings are not linearly spaced about the reference frequency (Espinosa et al. 2004). Recent studies (Reese et al. 2009a; Deupree & Beslin 2010;

**Table 3**

V 589 Mon: 37 Pulsation Frequencies (Freq) Identified from the *CoRoT* Data with Their Respective Last Digit Errors Given in Parentheses, Amplitudes (amp), HBR Where Appropriate, a Flag for Frequencies also Present in the *MOST* 2004 and 2006 Data Sets (*MOST*) and the Cross-identification to the Previously Published 12 Frequencies (Gue09; Guenther et al. 2009)

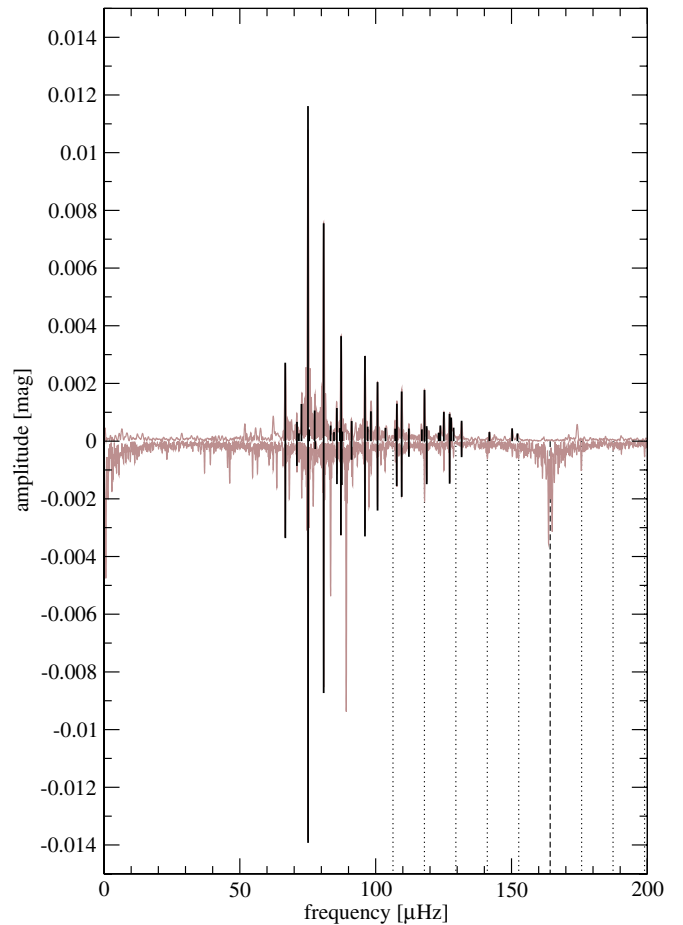
No.	Frequency ( $d^{-1}$ )	Frequency ( $\mu\text{Hz}$ )	amp (mmag)	HBR Power	<i>MOST</i> y/n	Gue09 No.
F1	6.4884(5)	75.097(6)	11.615		y	F1
F2	6.9862(6)	80.859(6)	7.551		y	F2
F3	7.5426(8)	87.299(9)	3.640		n	...
F4	8.3005(9)	96.07(1)	2.954		y	F3
F5	5.7643(9)	66.72(1)	2.719		y	F4
F6	8.698(1)	100.68(1)	2.048		y	F5
F7	10.192(1)	117.97(1)	1.773		y	F6
F8	9.467(1)	109.57(1)	1.720		y	F7
F9	9.314(1)	107.80(2)	1.299		y	F9
F10	6.281(1)	72.70(1)	1.287		y	F8
F11	7.407(1)	85.73(2)	1.147		n	...
F12	6.699(1)	77.54(2)	1.063		y	F12
F13	8.490(1)	98.26(2)	1.036		n	...
F14	10.809(1)	125.10(2)	1.007		n	...
F15	10.990(1)	127.20(2)	0.945		y	F11
F16	11.043(1)	127.81(2)	0.816	25.6	n	...
F17	11.372(2)	131.62(2)	0.706	21.6	y	...
F18	7.876(2)	91.16(2)	0.696	20.5	y	...
F19	6.138(2)	71.04(2)	0.670	19.3	y	...
F20	10.697(2)	123.81(2)	0.543	17.0	n	...
F21	7.205(2)	83.40(2)	0.540	16.1	n	...
F22	10.262(2)	118.78(2)	0.517	15.7	y	F10
F23	8.386(2)	97.06(2)	0.501	15.2	n	...
F24	11.119(2)	128.70(2)	0.468	13.8	n	...
F25	8.953(2)	103.62(2)	0.456	13.4	n	...
F26	7.503(2)	86.84(2)	0.455	13.6	n	...
F27	12.980(2)	150.23(2)	0.442	15.3	n	...
F28	9.698(2)	112.24(2)	0.437	13.5	y	...
F29	9.260(2)	107.17(2)	0.431	12.8	n	...
F30	10.109(2)	117.00(2)	0.408	12.6	n	...
F31	6.524(2)	75.51(2)	0.405	11.4	n	...
F32	7.579(2)	87.72(3)	0.333	10.0	y	...
F33	12.257(2)	141.87(3)	0.314	10.2	n	...
F34	7.313(3)	84.65(3)	0.313	9.1	n	...
F35	10.643(3)	123.18(3)	0.290	10.1	n	...
F36	6.199(3)	71.74(3)	0.270	11.1	n	...
F37	13.148(3)	152.18(3)	0.267	9.5	n	...

**Note.** The first 15 frequencies with the respective highest amplitudes were prewhitened before granulation modeling.

Ouazzani 2008) show that non-perturbative multi-dimensional approaches are necessary to predict the frequency spacings. Although the direct modeling of these frequencies is complicated, Reese et al. (2009b) show how an empirical formula can be used to fit the frequencies assuming the interior rotation profile is simple enough. Needless to say, as long as mode identification depends on the interior rotation curve, there will always be some ambiguity in the actual identifications.

Finally, we note that the observed frequencies are low, corresponding to model modes near the fundamental frequency of the star. Although the frequencies of these modes are more sensitive to the interior structure of the star than higher frequency modes, hence, better suited to constraining the evolutionary state of the model, they are also subject to a mode bumping-like effect. As a consequence, the regular spacing between adjacent  $p$ -modes is perturbed, hindering mode identification.

In the following section, we provide a general overview of the modeling methodology and theoretical considerations used



**Figure 5.** Comparison of the V 589 Mon amplitude spectra (gray) derived from *CoRoT* (oriented upward) and *MOST* 2004 (negative values assigned) data where the respective 37 and 17 pulsation frequencies are identified in black; the dashed line marks the *MOST* orbital frequency and the dotted lines are the respective  $1 d^{-1}$  sidelobes.

(A color version of this figure is available in the online journal.)

to interpret the oscillation spectra. In Sections 4.2. and 4.3., we discuss each star separately beginning with V 589 Mon.

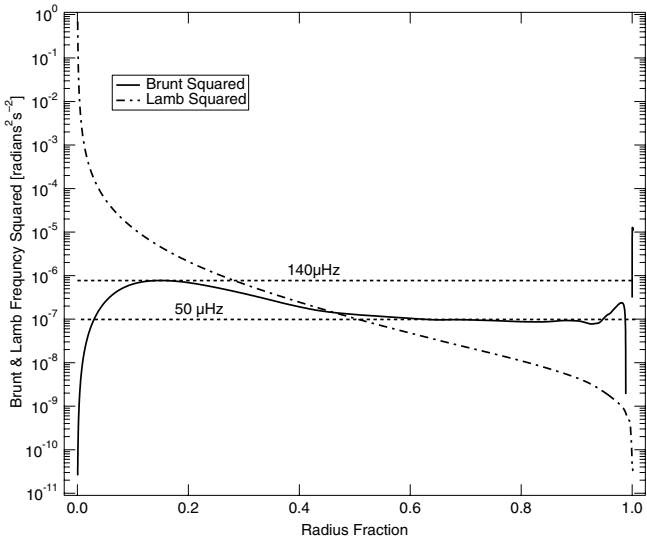
## 4.1. Method

### 4.1.1. Stellar Mode and Model Calculation

All of our modeling and seismic analyses are based on a dense set of models that cover the HR diagram. The PMS models start above the birthline on the Hayashi track and extend to the ZAMS. Model masses range from  $0.81 M_{\odot}$  to  $4.99 M_{\odot}$  in increments of  $0.01 M_{\odot}$ . The models themselves were constructed using the Yale Stellar Evolution Code (YREC; Demarque et al. 2008) incorporating the latest opacities, nuclear physics, and equation of state. Each model is resolved into  $\sim 2000$  shells with two-thirds of the shells covering the outer envelope and Eddington gray atmosphere. We estimate the model frequency uncertainty to be 0.1%. The grid density is such that  $\sim 2000$  models lie within  $2\sigma$  of each star's position in the HR diagram, of the  $\sim 400,000$  models computed in total (Guenther et al. 2009).

The adiabatic  $p$ -mode frequencies for  $l = 0, 1, 2,$  and  $3$  of the models were computed using Guenther's stellar pulsation code (Guenther 2004). We have assumed that geometric cancellation will occur for higher-order  $p$ -modes making them more difficult





**Figure 6.** Propagation diagram for the interior model of V 589 Mon. The square of the Brunt Väisälä and Lamb frequencies, in units of  $\text{rad}^2 \text{s}^{-2}$ , is plotted against the radius fraction.

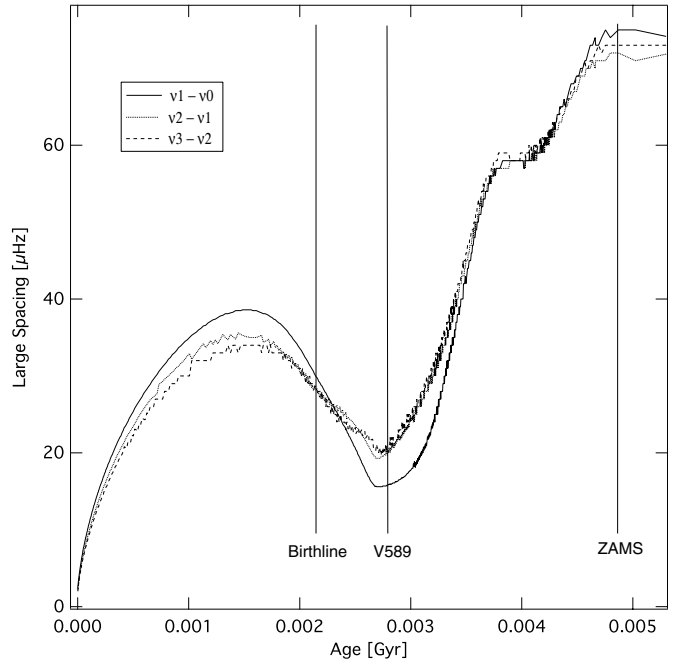
to see above the background noise level (see discussion in Section 3.1).

#### 4.1.2. Mode Bumping in PMS Stars

When the oscillation frequencies of our PMS models are plotted in an echelle diagram (i.e., frequency modulo the large spacing plotted opposite the frequency of the modes), they reveal the vertical alignment characteristic of common  $l$ -valued  $p$ -modes. But maybe surprising at first glance, the lowest radial order,  $n$ , modes do not stay aligned with the modes at higher frequencies but zigzag. This behavior is common to evolved post-main sequence stars and is attributed to the increased density gradients in the region surrounding the isothermal helium core near the base of the hydrogen burning shell. The effect is called mode bumping and is well documented in texts on stellar pulsation (e.g., Cox 1980; Unno et al. 1989). PMS stars do not show the same large gradients in density because nuclear burning has not yet begun.

Regardless, for some PMS stars there exists a slight peak in the Brunt–Väisälä frequency in the deep interior (see Figure 6 for V 589 Mon). This bump is enough to perturb the  $p$ -mode eigenfunction in the interior and affects its frequency. Note, only nonradial  $p$ -modes show mode bumping since they need to couple with  $g$ -modes (for which  $l = 0$  modes are undefined). The perturbation in frequency can be seen in a plot of  $p$ -mode frequency versus (evolutionary) time as shown in Figure 7 for  $l = 1$   $p$ -modes for models along a  $2.65 M_{\odot}$  track (corresponding to V 589 Mon, see Section 4.2.). The large spacing varies as the star evolves, changing inversely with the radius of the star. The  $n = 0$  large spacing deviates slightly from the large spacing of the other modes at various times during the evolution of the star.

Unlike the mode bumping that is seen in post-main sequence stars, the PMS bumping does not occur abruptly in time: it is only slowly varying as the model evolves toward the ZAMS. Consequently, it is not necessary to increase the resolution of the grid to follow this behavior as is the case of post-main sequence bumping. Although it complicates the identification of the modes at low frequencies, it also provides an additional feature of the oscillation spectrum that can be used to confirm the interior structure and evolutionary state of the PMS model.



**Figure 7.** Time evolution of the large frequency spacing of the lowest  $n$ -valued,  $l = 0$   $p$ -modes for a  $2.65 M_{\odot}$  PMS model track (which passes through V 589 Mon's position in the HR diagram). The frequency difference between the  $n = 1$  and  $n = 0$   $p$ -modes is drawn with a solid line (indicated in the legend by  $v_1 - v_0$ ). The frequency differences between the  $n = 2$  and  $n = 1$ , and  $n = 3$  and  $n = 2$  are drawn with dashed lines (as labeled in the legend). The birthline, the ZAMS, and the point where the track passes through V 589 Mon are indicated.

#### 4.1.3. Searching for the Best-fitting Model Spectra

To find the best-fit model oscillation spectrum to the observed spectrum, we searched our grid of models (Guenther & Brown 2004) looking for local minima in  $\chi^2$  defined by

$$\chi^2 = \frac{1}{N} \sum_{i=1}^N \frac{(v_{\text{obs},i} - v_{\text{mod},i})^2}{\sigma_{\text{obs},i}^2 + \sigma_{\text{mod},i}^2}, \quad (1)$$

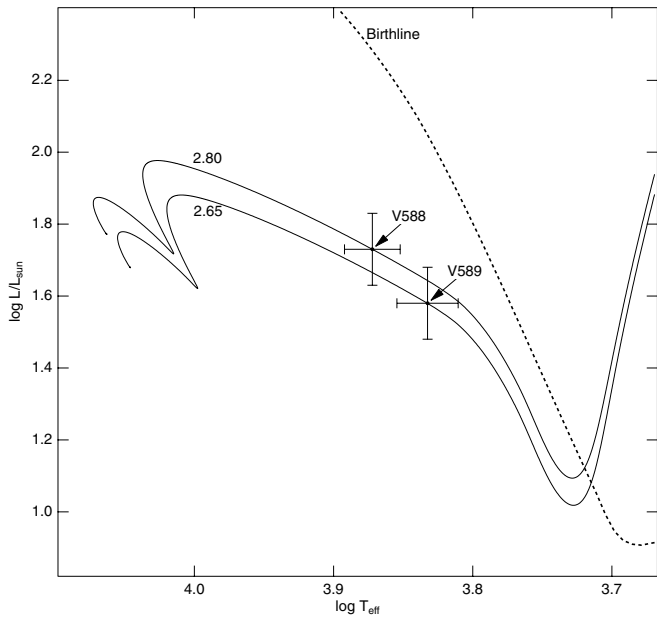
where  $v_{\text{obs},i}$  is the observed frequency for the  $i$ th mode,  $v_{\text{mod},i}$  is the corresponding model frequency,  $\sigma_{\text{obs},i}$  is the observational uncertainty for the  $i$ th mode, and  $N$  is the total number of modes that match the observed frequencies. We estimate the model uncertainty  $\sigma_{\text{mod},i}$  by fitting models to the solar oscillation spectrum (Guenther 2004). Here, we set it to 0.1% of the frequency of the mode.

#### 4.1.4. Rotation

As we will describe in Sections 4.2. and 4.3., we were unsuccessful in finding  $p$ -mode frequency fits to all the observed modes. Owing to the not insignificant rotation rates of the two stars, we considered the possibility that the oscillation spectrum of each star contains rotationally split modes. We included only the lowest order approximations in these attempts since full nonlinear rotational splitting computations are too laborious to be applied to a grid searching methodology.

As a first attempt we considered a range of fixed width splittings. These are not model-constructed splittings that depend on the eigenfunction of the mode and the interior structure, but are simply a constant frequency added to and subtracted from the model frequency in order to simulate, approximately, the expected set of frequency splittings. In other words, when searching our grid of models we looked for frequency matches





**Figure 8.** Locations of V 588 Mon and V 589 Mon in the HR diagram. The birthline,  $2.65 M_{\odot}$ , and  $2.80 M_{\odot}$  PMS evolutionary tracks are shown.

between model and observations at  $\nu \pm m\Delta\nu$ , where  $\nu$  is a model computed  $p$ -mode,  $m$  is the order of the splitting, and  $\Delta\nu$  is the splitting frequency itself.

We also computed rotational splittings for a selected set of models, using the formulation of Gough (1981), for a solid body rotation curve and for a rotation curve that rises near the surface. Here we wanted to see if we could perceive any difference between the two different rotation curves, e.g., one curve produced slightly lower  $\chi^2$  spectrum fits than the other. Note that Gough’s formula is applicable to slow rotation rates only.

#### 4.2. V 589 Mon

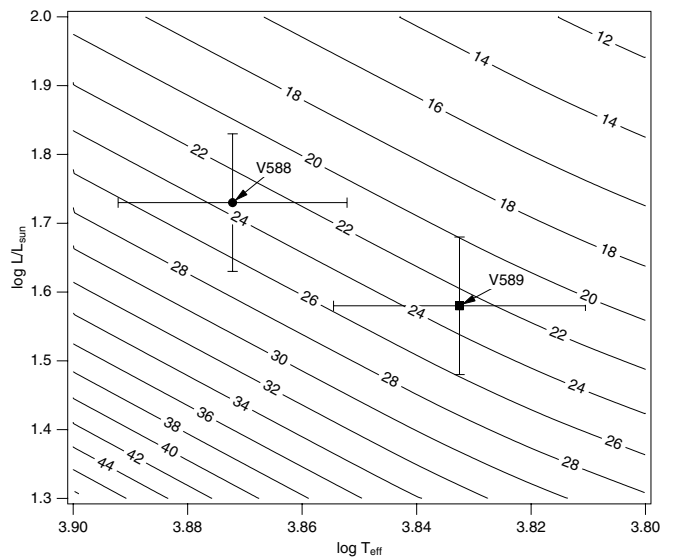
##### 4.2.1. Observational Constraints

V 589 Mon is located just below the birthline in the HR diagram along our  $2.65 M_{\odot}$  PMS evolutionary track as shown in Figure 8. Note that its location in the HR diagram and its association with the cluster NGC 2264 preclude it from being a post-main sequence star. The birthline (Stahler 1983; Palla & Stahler 1999) corresponding to a mass in-fall rate of  $\sim 10^{-5} M_{\odot} \text{ yr}^{-1}$  is shown. Following Guenther et al. (2009) we take the luminosity of V 589 Mon to be  $\log L/L_{\odot} = 1.58 \pm 0.1$ , the effective temperature to be  $6800 \pm 350 \text{ K}$ , and note that the observed  $v \cdot \sin i$  is  $60 \pm 10 \text{ km s}^{-1}$  (see Kallinger et al. 2008b, their Table 2, values adopted from Two Micron All Sky Survey (2MASS) photometry).

##### 4.2.2. Mode Analysis

Figure 9 shows the model-computed characteristic spacing (approximately equal to the average large spacing in the asymptotic limit of large radial order  $n$ , Tassoul 1980) as a function of position in the HR diagram in the vicinity of V 589 Mon (and V 588 Mon). The average small spacing, over the observed frequency range, computed from our model grid is  $1.7 \pm 0.3 \mu\text{Hz}$ .

We plot the observed frequencies in an echelle diagram to reveal the vertical alignment characteristic of common  $l$ -valued  $p$ -modes. Models show that the regular spacing between  $p$ -modes extends all the way to  $n = 1$  for PMS stars. Based on the



**Figure 9.** Contour plot of characteristic spacing (asymptotic large spacing), in units of  $\mu\text{Hz}$ , computed from PMS models near V 588 Mon’s and V 589 Mon’s locations in the HR diagram as indicated by the uncertainty bars.

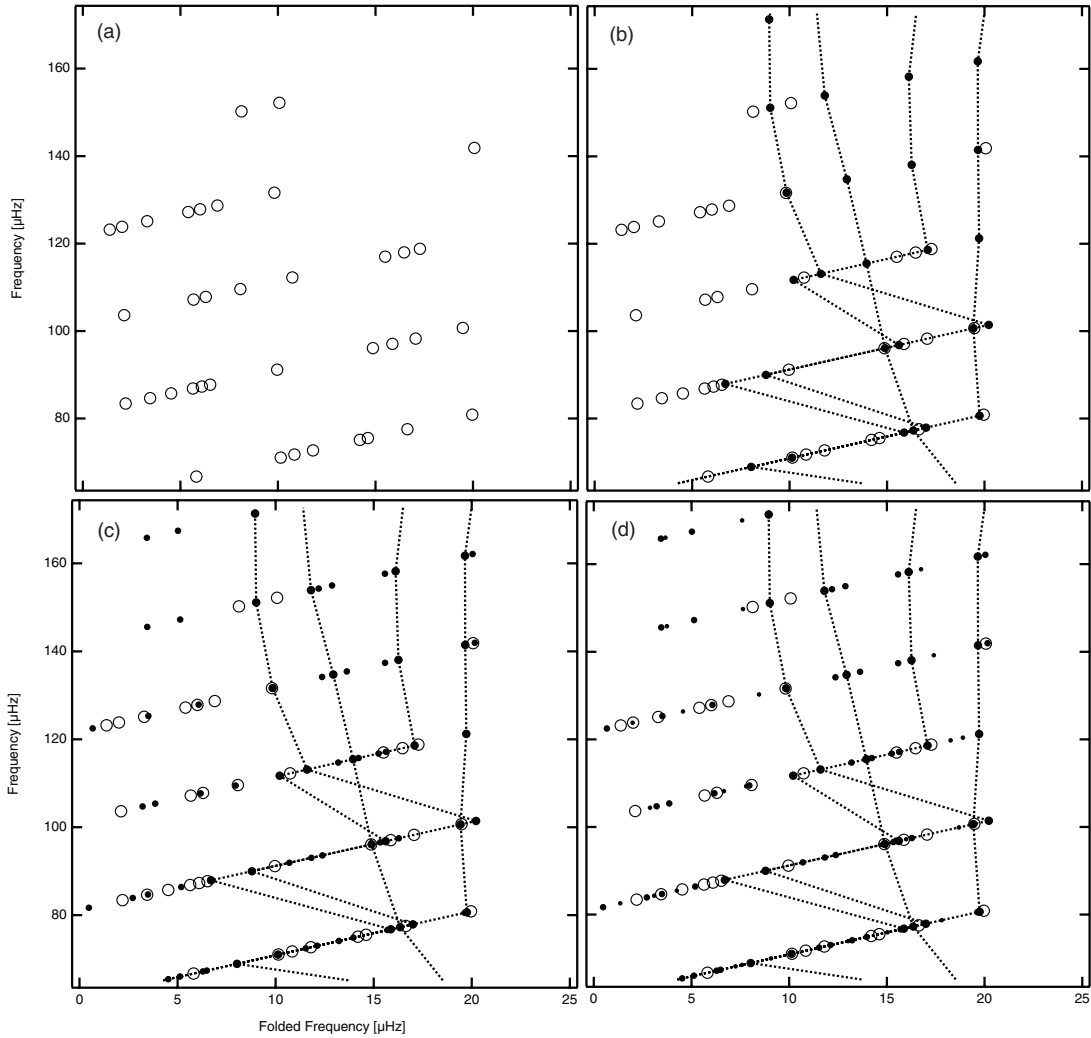
model results shown in Figure 9, we see that the large spacing for V 589 Mon should lie between  $20 \mu\text{Hz}$  and  $26 \mu\text{Hz}$ . The *CoRoT* frequencies have amplitudes down to  $0.27 \text{ mmag}$  where the *MOST* frequencies have amplitudes at or above  $0.46 \text{ mmag}$ . Note that this set of *MOST* frequencies includes low-amplitude frequencies that were excluded in the analysis of Guenther et al. (2009) where only the eight frequencies common to *MOST* and ground-based observations were presented and analyzed. We proceed with our model analysis using the *CoRoT* frequencies.

In an echelle diagram, there is some suggestion for vertically aligned sequences of modes in the observations, but the effect is confused by the presence of many additional apparently randomly scattered frequencies (see Figure 10). What strikes us most are the many more frequencies observed by *CoRoT* between  $50 \mu\text{Hz}$  and  $150 \mu\text{Hz}$  than can be accounted for from just  $l = 0, 1, 2$ , and  $3 p$ -modes. As noted in Section 4.1, we believe that geometric factors and the limited S/N of our data rule out the possibility of identifying higher  $l$  values in our *CoRoT* (and *MOST*) data.

We searched through all  $\sim 400,000$  PMS models in our grid comparing their oscillation spectra to the observed spectrum and identified those models that had  $\chi^2 \leq 1$ . We could find no model whose oscillation spectrum fits (with  $\chi^2 \leq 1$ ) more than nine of the 37 frequencies at a time with  $l = 0, 1, 2$ , and  $3 p$ -modes and which falls within the uncertainty box of V 589 Mon’s position in the HR-diagram. The observed frequencies cannot all be accounted for by  $l = 0, 1, 2$ , and  $3 p$ -modes alone.

##### 4.2.3. Rotation

To account for the extra modes present in the observed frequency range, we consider the possibility that rotationally split frequencies are present. An autocorrelation plot of the observed spectrum (Figure 11) shows a strong broad peak at  $4.1 \mu\text{Hz}$  ( $f_1$ ), with lesser peaks at  $7.9 \mu\text{Hz}$  ( $\sim 2f_1$ ),  $20.2 \mu\text{Hz}$  ( $f_2 \sim \text{large spacing}$ ),  $15.8 \mu\text{Hz}$  ( $f_2 - f_1$ ), and  $24.5 \mu\text{Hz}$  ( $f_2 + f_1$ ). We speculate that the  $4.1 \mu\text{Hz}$  peak is due to  $m = \pm 1$  rotational splittings and that the  $7.9 \mu\text{Hz}$  peak is due to the  $m = \pm 2$  rotational splittings. Recall that the small spacing as determined from our models is  $\sim 1.7 \mu\text{Hz}$ , and hence cannot explain the  $4.1 \mu\text{Hz}$  peak, unless, of course, the deep interior structure of

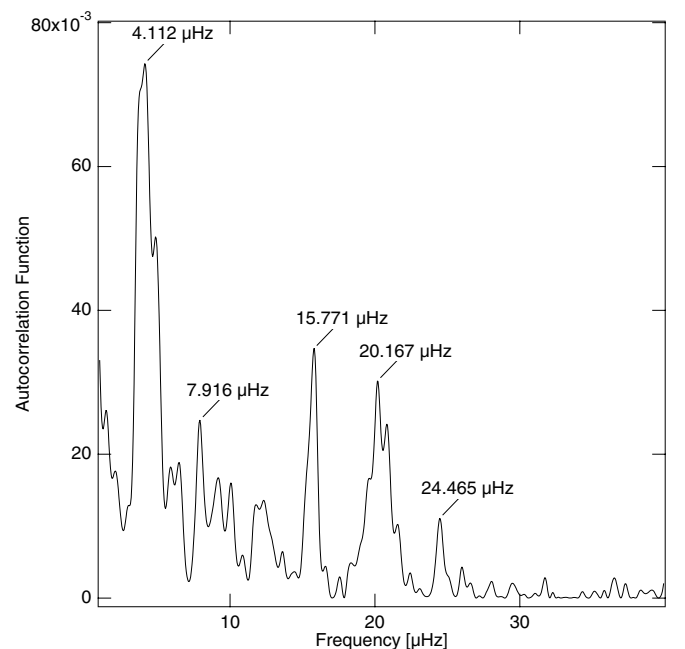


**Figure 10.** Echelle diagrams for V 589 Mon with folding frequency  $20.3 \mu\text{Hz}$ . Each panel adds in sequence, starting with the *CoRoT* observed frequencies in (a), the model  $l = 0, 1, 2,$  and  $3$   $p$ -modes in (b), the  $m = \pm 1$  model rotational split frequencies in (c), and the  $m = \pm 2$  model rotational split frequencies in (d).

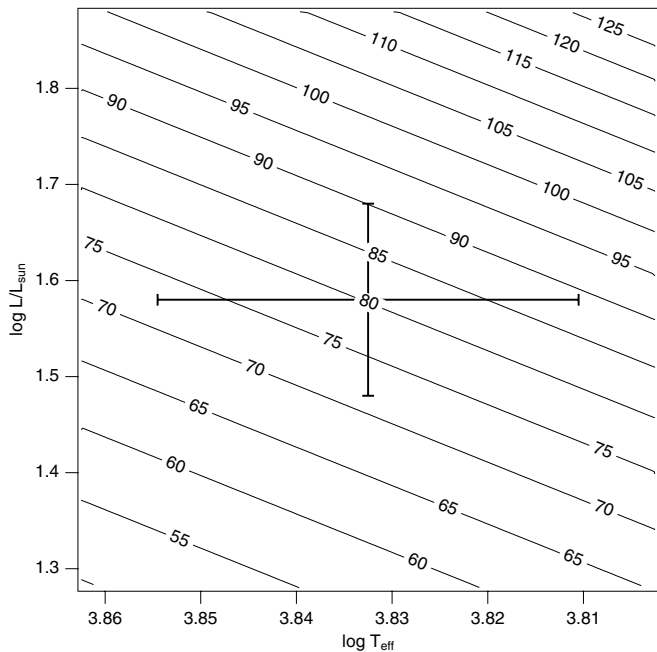
our models is grossly wrong. That the small spacing peak is not visible also supports our belief that high  $l$ -valued modes are not present in this data set. The equatorial velocities,  $v_{\text{rot}}$ , corresponding to a  $4.1 \mu\text{Hz}$  splitting produced by solid body rotation for models near V 589 Mon's location in the HR diagram are shown in Figure 12. The rotation rate implied by the splitting frequency is consistent with the observed  $v \cdot \sin i$  of  $60 \pm 10 \text{ km s}^{-1}$ .

First, to show how rotationally split modes fill up the echelle diagram, we computed rotational splittings, assuming solid body rotation (corresponding to  $\sim 4 \mu\text{Hz}$  splitting), for the model located closest to V 589 Mon's HR diagram position, using the formulation from Gough (1981). In Figure 10, we show the *CoRoT* observations, (a)–(d), along with the unsplit model modes, (b)–(d), the  $m = \pm 1$  splittings, (c) and (d), and the  $m = \pm 1, \pm 2$  splittings. The number density and distribution of model modes are a best match when the rotational splittings are included. But clearly there is no direct correspondence between the model frequencies and the observations.

We repeated our  $\chi^2$  search but used oscillation spectra that include a fixed width rotational splitting, which we varied from  $2.5 \mu\text{Hz}$  to  $7.5 \mu\text{Hz}$  in steps of  $0.1 \mu\text{Hz}$ . Restricting our search to  $m = 0, \pm 1$  splittings, we could find, in the best case, matches to 22 of the 37 frequencies at one time and lie within the uncertainty



**Figure 11.** Autocorrelation plot of the oscillation frequency spectrum of V 589 Mon observed by *CoRoT* with the frequencies of the highest peaks labeled.

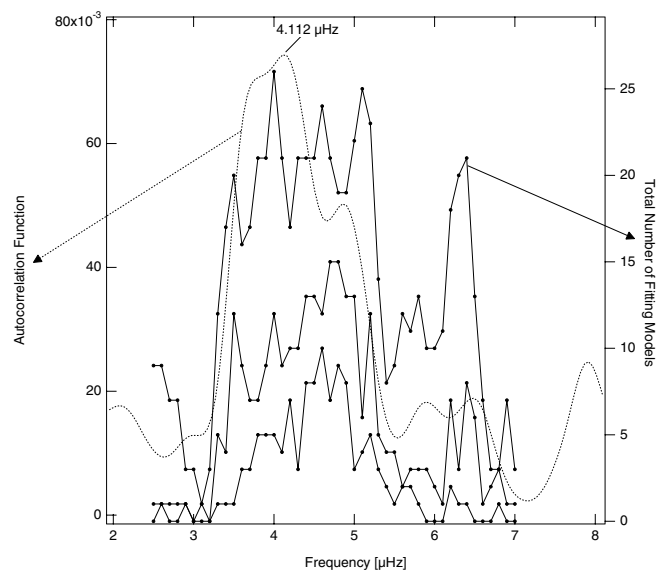


**Figure 12.** Equatorial rotational velocities in units of  $\text{km s}^{-1}$  are shown in the vicinity of V 589 Mon’s HR-diagram location. The rotational velocities are computed (they depend on the model radius) for a rotational splitting (solid body) of  $4.1 \mu\text{Hz}$ .

box of V 589 Mon’s position in the HR diagram. The splitting frequency of the best case match is  $4.5 \mu\text{Hz}$ . For  $m = \pm 1, \pm 2$  splittings, we could find model fits to 24 of the frequencies again with a splitting frequency equal to  $4.5 \mu\text{Hz}$ . If we assume that we are seeing rotational split modes, the small difference between fitting just  $m = \pm 1$  and  $m = \pm 1, \pm 2$  modes suggests that, as expected,  $m = \pm 2$  (and  $m = \pm 3$ ) rotationally split frequencies are not as prominent in the observations as the  $m = \pm 1$  modes.

In a crude attempt to show that the model fits do indeed prefer a splitting near  $4.5 \mu\text{Hz}$ , we computed the number of models whose oscillation spectra match exactly 17, 18, and 19 modes, of the 37 observed, and that also lie inside V 589 Mon’s uncertainty box in the HR diagram. When plotted as a function of the splitting frequency, Figure 13, we see that the number of models that fit the observations peaks for rotational splittings between 4 and  $5 \mu\text{Hz}$ . The frequency dependence of the number of model fits matches the autocorrelation function. There is also a peak at  $6.5 \mu\text{Hz}$ . This peak is likely the combined effect of the  $l = 0$  small spacing and the rotational splitting. Although we cannot extract any statistical quantities from this plot since the model count scale is arbitrary and depends on the density of models in our grid, it does show that models that have rotational splittings outside the range from  $4 \mu\text{Hz}$  to  $5 \mu\text{Hz}$  do not fit the data as well as those within this range of splittings consistent with our interpretation that the observed spectrum contains sidelobes of rotationally split modes.

That we are not able to fit all of the observed modes with our models may, in part, be due to the fact that we assumed the splitting frequency is constant, when, in fact, we know that the splitting does depend on model structure, the interior rotation curve, and the eigenfunction of the mode itself. To get a sense of how important these effects are we computed rotational splittings for a solid body rotation curve and for a rotation curve in which the angular velocity is constant throughout the interior then linearly increases by a factor almost a factor of two over the



**Figure 13.** Autocorrelation plot for *CoRoT* observations of V 589 Mon (dashed line) compared to the number of models that fit 17, 18, and 19 of the 37 observed frequencies for a given autocorrelation frequency ( $\mu\text{Hz}$ ), and that lie within the uncertainty box of V 589 Mon’s position in the HR diagram. The lowest curve (solid line joining points) corresponds to the number of models fitting 19 frequencies. The next lowest curve corresponds to the number of models fitting 18 frequencies and the highest curve corresponds to the number of models fitting 17 frequencies.

outer 2% radius of the star, using the formula by Gough (1981), which is applicable to slow rotation rates.

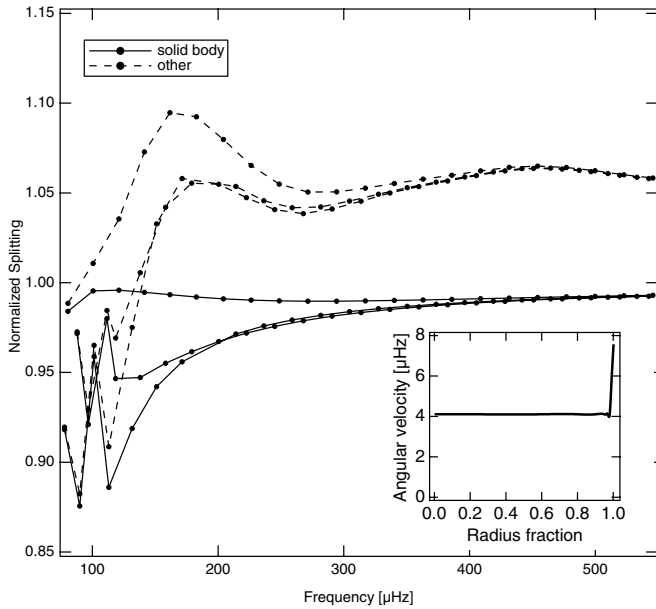
In Figure 14, we plot the splitting frequency normalized to the surface rotation rate frequency as a function of frequency for  $l = 1, 2$ , and  $3 p$ -modes. The rotational splitting is constant except at lowest frequencies where from mode to mode it varies by about 10%. Coincidentally, this is the frequency range over which the oscillation frequencies for V 589 Mon are observed. At low frequencies the variation for a  $4 \mu\text{Hz}$  splitting is  $\sim 0.4 \mu\text{Hz}$ . Since we have taken our modeling uncertainty to be 0.1%, which corresponds to frequency uncertainty of  $0.1 \mu\text{Hz}$  for a  $100 \mu\text{Hz}$  mode, our model fits should be sensitive to the variation in splitting with frequency.

To test if we could see any difference in our  $\chi^2$  searches, we computed a new model pulsation grid that includes the frequency-dependent splittings for each mode assuming a solid body internal rotation curve. For a solid body rotation rate corresponding to a  $4.1 \mu\text{Hz}$  rotation rate at the equator of the star, we did not find any significantly better or poorer model fits than our constant frequency splittings test at  $4.1 \mu\text{Hz}$ . Due to the more laborious nature of these more refined model fits and their dependence on the internal rotation curve itself, we have not yet pursued more thorough searches over a wide range of rotation rates and rotation curves. We believe that a different strategy is needed.

### 4.3. V 588 Mon

#### 4.3.1. Observational Constraints

V 588 Mon is located just below the birthline in the HR diagram along a  $2.80 M_{\odot}$  PMS evolutionary track, as shown in Figure 8. Following Guenther et al. (2009) we take the luminosity of V 588 Mon to be  $\log L/L_{\odot} = 1.73 \pm 0.1$ , the effective temperature to be  $T_{\text{eff}} = 7450 \pm 350 \text{ K}$ , and the observed  $v \cdot \sin i$  is  $130 \pm 20 \text{ km s}^{-1}$  (see Kallinger et al. 2008b, their Table 2, values adopted from 2MASS photometry). Except



**Figure 14.** Normalized rotational splittings ( $\Delta\nu/\nu$ ) as a function of frequency in  $\mu\text{Hz}$ ,  $\nu$ , computed from a model of V 589 Mon for solid body rotation (solid line) and for the rotation curve shown in the inset (dashed line).

for the higher  $v \cdot \sin i$ , the star appears to be similar to V 589 Mon.

#### 4.3.2. Mode Analysis

Figure 9 shows the expected large spacing as obtained from our model grid in the vicinity of V 588 Mon’s location in the HR diagram. Accordingly, we use a folding frequency of  $22 \mu\text{Hz}$  in our echelle diagrams for V 588 Mon.

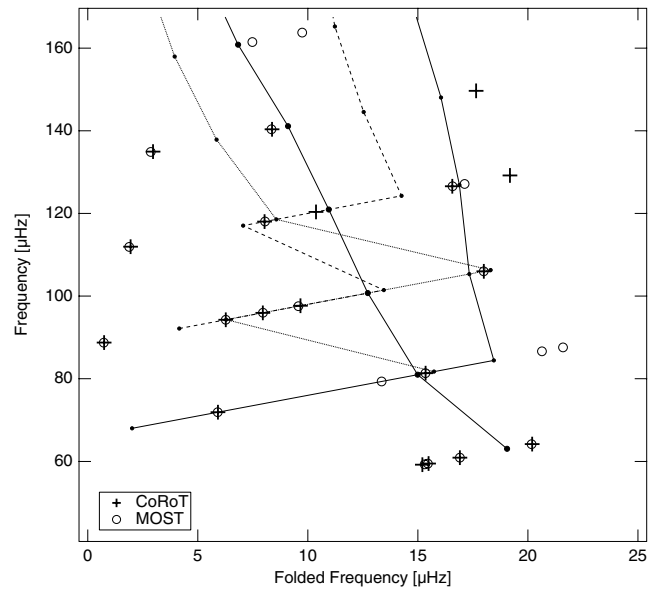
We identify 14 significant frequencies in the *CoRoT* observations above an amplitude of 0.5 mmag. *MOST* detects 24 significant frequencies above this amplitude. As with the *MOST* data for V 589 Mon, we have included all significant modes not just those selected by Guenther et al. (2009) found in both ground and *MOST* data. The *CoRoT* and *MOST* sets of frequencies are shown in the echelle diagram of Figure 15. Our model analysis is restricted to the *CoRoT* frequencies. We also plot the  $l = 0, 1, 2,$  and  $3 p$ -modes for the model in our grid that lies closest to V 588 Mon’s location in the HR diagram.

There is some suggestion of vertical alignment in the observed frequencies as seen in the echelle diagram. But unlike V 589 Mon, the distribution and density of modes do not point to an obvious overabundance of frequencies.

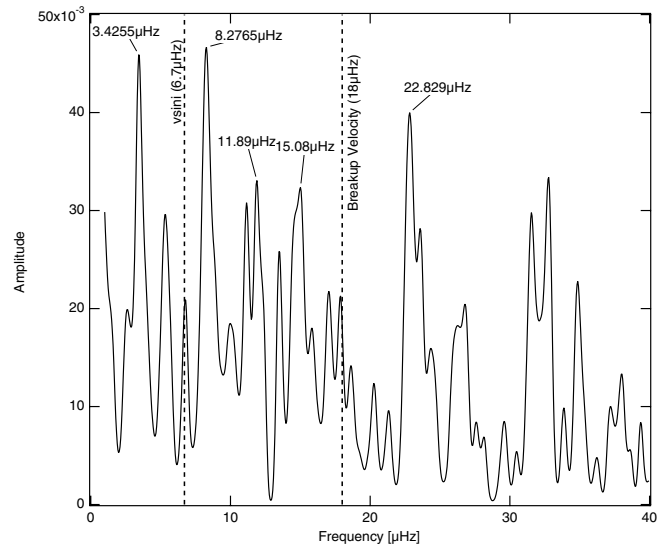
As with V 589 Mon, we first sought model fits with  $l = 0, 1, 2,$  and  $3 p$ -modes to the observed frequencies (excluding rotational splittings). We were only able to find models lying with the HR-diagram uncertainty box for V 588 Mon that fit more than four (of the 14 *CoRoT* modes) with  $\chi^2 \leq 1$ . Indeed, for fits to five of the frequencies, no models within  $2\sigma$  of the star’s HR-diagram location were found. Again we are led to believe the extra modes are rotational splittings.

#### 4.3.3. Rotation

Figure 16 shows the autocorrelation function for V 588 Mon’s oscillation spectrum. The observed  $v \cdot \sin i$  sets a lower limit on the possible rotational splittings of  $\sim 6.7 \mu\text{Hz}$  (assuming that V 588 Mon’s location in the HR diagram is correct) and the breakup velocity (where the centripetal acceleration at the equator equals the gravitational acceleration at the surface) sets



**Figure 15.** Echelle diagram showing all the significant frequencies observed by *CoRoT* and *MOST* of V 588 Mon falling between  $50 \mu\text{Hz}$  and  $175 \mu\text{Hz}$ . The folding frequency is  $22 \mu\text{Hz}$ . The  $l = 0, 1, 2,$  and  $3 p$ -modes of the model that fall closest to V 588 Mon’s position in the HR diagram are indicated by a solid line connecting large points, a solid line connecting smaller points, a short dashed line connecting smaller points, and a long dashed line connecting smaller points, respectively.



**Figure 16.** Autocorrelation plot of the oscillation frequency spectrum of V 588 Mon observed by *CoRoT* with the frequencies of the highest peaks labeled. The lower limit to the splitting frequency set by the observed  $v \cdot \sin i$  and the splitting frequency corresponding to the equatorial breakup velocity are also indicated.

an upper limit on the splitting of  $\sim 18 \mu\text{Hz}$  (again assuming that the model parameters based on V 588 Mon’s location in the HR diagram are correct). The autocorrelation plot does not reveal any obvious splitting peak, although the large spacing frequency does appear to be present at  $\sim 23 \mu\text{Hz}$ . The possible splitting peaks are located at  $8.3 \mu\text{Hz}$ ,  $11.9 \mu\text{Hz}$ , and  $15.1 \mu\text{Hz}$ . But clearly none stands out.

We carried out  $\chi^2$  searches with fixed rotational splittings ranging from  $5 \mu\text{Hz}$  to  $18 \mu\text{Hz}$  but unlike V 589 Mon did not find any preferred frequency splitting or range of splittings. We believe that the rotation rate is, in fact, high enough for nonlinear effects to be important. At high rotation rates, the centrifugal and Coriolis force terms become important



and introduce non-axisymmetric splittings. Deupree & Beslin (2010) have computed the oscillation spectra of rapidly rotating, massive ( $10 M_{\odot}$ ) ZAMS stars using a full 2.5-dimensional evolution code (see also Espinosa et al. 2004, who first show the complications of rotational splittings for rapid rotation). Deupree & Beslin's results are enlightening as they show that the autocorrelation function (or, equivalently, as used in their case, a Fourier transform of the oscillation spectrum) fails to show rotational splitting frequencies (see their Figure 6) already for stars with rotation rates at 10% breakup velocity. The rotational velocity of V 588 Mon as inferred from its  $v \cdot \sin i$  is minimally at 30% breakup velocity. If we assume that their results apply to our  $2.8 M_{\odot}$  PMS star, then we should expect to see an autocorrelation plot without any predominant splitting peaks (as we do). Deupree & Beslin (2010) also note that once the rotation rate is above 20% breakup velocity, the splittings from different modes begin to overlap each other further complicating mode identification. And so, our failure to find a model oscillation spectrum, even when including fixed value rotational splittings, may simply be a consequence of the far more complex nature of the splittings than our models are capable of addressing.

Rather than attempting to fit the frequencies with the asymptotic-like formula of Reese et al. (2009b), which they obtained from non-perturbative modeling of frequency splittings in rapidly rotating modes for simple rotation curves, we are pursuing a different approach that does not depend on any prior model or rotation curve assumptions. We will report on our results in a future publication.

## 5. CONCLUSIONS

The two pulsating PMS stars, V 588 Mon and V 589 Mon, were observed by *MOST* in 2004 and 2006 for in total  $\sim 70$  days and in 2008 by the *CoRoT* satellite for 23.4 days during the Short Run SRA01. Detailed frequency analyses were conducted for all available data sets and compared to each other.

Our analysis illustrates that the frequency-dependent intrinsic background signal, i.e., granulation, can explain a large number of significant peaks detected in PMS stars. Granulation modeling was conducted using a first-order model where two Lorentzian-like functions, white noise, and a Gaussian are combined. The resulting number of frequencies is more consistent with the expected number of low-degree  $p$ -modes observed in integrated light. But it was also shown that the shape of the pulsational power excess is very likely to be more complicated than a Gaussian and that a more sophisticated approach would be needed in the future. This effect is illustrated by the fact that for V 588 Mon, seven frequencies at low amplitudes would have been suppressed by the background noise model, but appear significantly in all three satellite data sets, i.e., in data from *MOST* 2004, *MOST* 2006, and *CoRoT*. If frequencies are stable over a period of four years, then they are unlikely to be caused by granulation.

After a comparison of the independent analyses of the *MOST* 2004 and *MOST* 2006 data sets to the *CoRoT* data, for V 588 Mon and V 589 Mon 21 and 37 frequencies, respectively, can be attributed to pulsation, among those the eight and 12 previously published frequencies (Guenther et al. 2009).

Even after granulation filtering, both V 588 Mon and V 589 Mon have more frequencies observed than can be accounted for by  $l = 1, 2,$  and  $3$   $p$ -modes. We investigated the possibility that the extra frequencies are rotational split modes. For V 589 Mon, the autocorrelation of the observed frequency spectrum and our model searches support the notion that rotational split

frequencies, with splittings between  $4 \mu\text{Hz}$  and  $5 \mu\text{Hz}$ , are present. We are able to match more than half of the observed frequencies with model fits. For V 588 Mon, the autocorrelation plot and our attempts to fit model spectra that included splittings were unsuccessful. We believe that this is because V 588 Mon's rotation rate is high enough (as implied by its  $v \cdot \sin i$ ) that its splittings are in the nonlinear regime as described by Espinosa et al. (2004), and further studied by Ouazzani (2008), Reese et al. (2009a), and Deupree & Beslin (2010).

How can we obtain unambiguous mode identifications for V 588 Mon and V 589 Mon when we do not know the interior rotation curve? Is inversion possible, i.e., in determining the rotation curve from the splittings, simultaneously with identifying the modes? Unlike the slowly rotating Sun, where the splittings are in the linear regime, V 588 Mon and V 589 Mon are rotating rapidly enough that non-perturbative models are probably necessary, especially for V 588 Mon. Rather than to continue with more sophisticated models, we are currently pursuing a different approach in which we apply a Bayesian approach that incorporates model-independent prior knowledge about the split and unsplit modes to estimate model fit likelihoods. We will report on our efforts in a future paper.

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## REFERENCES

- Aerts, C., et al. 2006, *ApJ*, **642**, 165  
 Baglin, A. 2006, The CoRoT Mission, Pre-launch Status, Stellar Seismology and Planet Finding ed. M. Fridlund, A. Baglin, J. Lochard, & L. Conroy (ESASP 1306; Noordwijk, The Netherlands: ESA Publications Division)  
 Breger, M. 1972, *ApJ*, **171**, 539  
 Breger, M., et al. 1993, *A&A*, **271**, 482  
 Christensen-Dalsgaard, J., & Gough, D. O. 1982, *MNRAS*, **198**, 141  
 Cox, J. P. 1980, *Theory of Stellar Pulsation* (Princeton, NJ: Princeton Univ. Press)  
 Daszyńska-Daszkiewicz, J., Dziembowski, W. A., & Pamyatnykh, A. 2006, *Mem. Soc. Astron. Ital.*, **77**, 113  
 Demarque, P., Guenther, D. B., Li, L. H., Mazumdar, A., & Straka, C. W. 2008, *Ap&SS*, **316**, 31  
 Deupree, R. G., & Beslin, W. 2010, *ApJ*, **721**, 1900  
 Espinosa, F., Pérez Hernández, F., & Roca Cortés, T. 2004, in Proc. SOHO14/GONG 2004 Workshop, ed. D. Danesy (ESASP 559; Noordwijk, The Netherlands: ESA Publications Division), 424  
 Gough, D. O. 1981, *MNRAS*, **196**, 731  
 Guenther, D. B. 2004, *ApJ*, **612**, 454  
 Guenther, D. B., & Brown, K. I. T. 2004, *ApJ*, **600**, 419  
 Guenther, D. B., Kallinger, T., Zwintz, K., Weiss, W. W., & Tanner, J. 2007, *ApJ*, **671**, 581  
 Guenther, D. B., et al. 2009, *ApJ*, **704**, 1710  
 Hog, E., et al. 2000, *A&A*, **355**, L27  
 Kallinger, T., & Matthews, J. M. 2010, *ApJ*, **711**, 35  
 Kallinger, T., Reegen, P., & Weiss, W. W. 2008a, *A&A*, **481**, 571  
 Kallinger, T., Zwintz, K., & Weiss, W. 2008b, *A&A*, **488**, 279  
 Kuschnig, R., Weiss, W. W., Gruber, R., Bely, P. Y., & Jenkner, H. 1997, *A&A*, **328**, 544  
 Lenz, P., & Breger, M. 2005, *CoAst.*, **146**, 53  
 Michel, E., et al. 2008, *Science*, **322**, 558  
 Michel, E., Samadi, R., Baudin, F., Barban, C., Appourchaux, T., & Auvergne, M. 2009, *A&A*, **495**, 979  
 Ouazzani, R.-M. 2008, *Commun. Asteroseismol.*, **157**, 356  
 Palla, F., & Stahler, S. W. 1999, *ApJ*, **525**, 772

- Poretti, E., et al. 2009, [A&A](#), **506**, 85
- Reegen, P., et al. 2006, [MNRAS](#), **367**, 1417
- Reese, D. R., MacGregor, K. B., Jackson, S., Skumanich, A., & Metcalfe, T. S. 2009a, [A&A](#), **506**, 189
- Reese, D. R., Thompson, M. J., MacGregor, K. B., Jackson, S., Skumanich, A., & Metcalfe, T. S. 2009b, [A&A](#), **506**, 183
- Rowe, J. F., et al. 2006, [ApJ](#), **646**, 1241
- Sagar, R., Piskunov, A. E., Miakutin, V. I., & Joshi, U. C. 1986, [MNRAS](#), **220**, 383
- Stahler, S. W. 1983, [ApJ](#), **274**, 822
- Strom, K. M., Strom, S. E., & Yost, J. 1971, [ApJ](#), **165**, 479
- Sung, H., Bessel, M. S., & Chun, M. Y. 2004, [AJ](#), **128**, 1684
- Tassoul, M. 1980, [ApJS](#), **43**, 469
- Unno, W., Osaki, Y., Ando, H., & Shibahashi, H. 1989, *Nonradial Oscillations of Stars* (2nd ed.; Tokyo: Univ. Tokyo Press)
- Walker, M. F. 1956, [ApJS](#), **2**, 365
- Walker, G., et al. 2003, [PASP](#), **115**, 1023
- Walker, G. A. H., et al. 2005, [ApJ](#), **635**, 77
- Weiss, W. 2006, in *Proc. The CoRoT Mission Pre Launch Status, Stellar Seismology and Planet Finding*, ed. M. Fridlund, A. Baglin, J. Lochard, & L. Conroy (ESASP 1306; Noordwijk, The Netherlands: ESA Publications Division), 93
- Zwintz, K. 2008, [ApJ](#), **673**, 1088
- Zwintz, K., et al. 2009, [A&A](#), **502**, 239