Singing comet waves in a solar wind convective electric field frame

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Abstract

The cometary plasma environment at low gas production rates is dominated by highly compressional, large amplitude magnetic field waves in the 10-100mHz range. They are thought to be caused by an ion-Weibel instability due to a cross-field current, which is caused by the cometary ions that are accelerated along the solar wind convective electric field. We devise a new method to determine the location of the wave detection, the wave power, frequency, and bandwidth. It is found that the wave occurs everywhere in the coma, regardless of electric field direction. There is no correlation between the wave frequency and the measured plasma density. This is not in agreement with previous studies. A dependence of the frequency on the position of the spacecraft in a comet-fixed frame is in agreement with the prediction from the ion-Weibel instability. We infer a wave generation region much larger than the distances covered by Rosetta.

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Key Points:

- Low-frequency waves may be found everywhere in the coma, regardless of the convective electric field direction.
- The wave frequency decreases with decreasing heliocentric distance.
- There is no correlation of the plasma density with the wave frequency.

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Abstract

The cometary plasma environment at low gas production rates is dominated by highly compressional, large amplitude magnetic field waves in the $10-100$ mHz range. They are thought to be caused by an ion-Weibel instability due to a cross-field current, which is caused by the cometary ions that are accelerated along the solar wind convective electric field. We devise a new method to determine the location of the wave detection, the wave power, frequency, and bandwidth. It is found that the wave occurs everywhere in the coma, regardless of electric field direction. There is no correlation between the wave frequency and the measured plasma density. This is not in agreement with previous studies. A dependence of the frequency on the position of the spacecraft in a comet-fixed frame is in agreement with the prediction from the ion-Weibel instability. We infer a wave generation region much larger than the distances covered by Rosetta.

Plain Language Summary

We study the properties and region of occurrence of so-called singing comet waves. This type of electromagnetic wave has only been observed at comet 67P/Churyumov-Gerasimenko at low gas production rates. Contrary to previous publications our results indicate that this wave is not only found in one hemisphere of the comet's plasma environment. Instead it is generated in a much bigger region around the nucleus than previously known.

1 Introduction

Comets are small solar system bodies composed of ices and rock. As comets approach the Sun, the ices sublimate and form a neutral gas coma around the nucleus that is not gravitationally bound. The gas is ionized mainly by photo-ionization and electron impact ionization. The resulting ion cloud presents an obstacle to the solar wind, as the newly formed ions are at rest in the cometary frame of reference. To incorporate the cometary ions into the solar wind they need to be accelerated which may be accomplished by an $E \times B$ drift that is associated with the convective electric field of the solar wind (Behar et al., 2016). As the cometary ions are mainly water and the solar wind magnetic field magnitude is low, the gyroradius of the cometary ions can exceed 10000 km under low outgassing conditions at high heliocentric distances (Glassmeier, 2017).

The Jupiter family comet 67P/Churyumov-Gerasimenko was explored by the European Space Agency's Rosetta mission for an entire perihelion passage from 2014 to 2016 (Glassmeier, Boehnhardt, et al., 2007). The spacecraft was equipped with a full suite of plasma instruments that explored the interaction of the solar wind with the cometary charged particle environment.

Since its arrival at the comet, Rosetta has measured various plasma waves, most notably a new type of low frequency wave in the vicinity of a weakly outgassing comet was found by Richter et al. (2015). They show that large amplitude, compressional waves are detected around frequencies of 40 mHz. The wave frequency does not depend on the background magnetic field. This type of wave is new compared to observations at other comets, where a wave in the frequency range of the ion-cyclotron frequency (which depends on the magnetic field magnitude) was detected. Richter et al. (2015) find that the "wave activity in general is controlled by the cometary ion production rate" and that the magnetic energy density in the $30-80$ mHz band increases with decreasing cometocentric distance down to a distance of about 30 km. The proposed generation mechanism for this wave activity is a cross-field current. This mechanism is further investigated theoretically by Meier et al. (2016), who find a zero frequency wave that is subject to a Doppler shift to the spacecraft frame of reference.

Richter et al. (2016) and Heinisch et al. (2017) study the properties of these waves using both Rosetta and the lander Philae's observation of the magnetic field. They find that both spacecraft measure the same wave phenomena, indicating that the generation region is larger than the separation ($\sim 10\,\text{km}$) of the two spacecraft. They infer a wavelength of tens to hundreds of km and show that the wave signature is broadband and variable between $\sim$ 10 mHz and $\sim$ 100 mHz. They report an upper size limit for the generation region of 100 km.

Simulations of the plasma environment of a weakly outgassing comet reveal structures that can be interpreted as waves (Koenders et al., 2016). They are exclusively found in the $+E$ hemisphere of the interaction region, where E is the solar wind convective electric field. A second simulation reveals that even at higher gas production rates, the waves are present and confined to one hemisphere.

Hajra et al. (2017) investigate the plasma's reaction to a cometary outburst (Grün et al., 2016). It is found that the singing comet waves vanish around the time of the highest plasma density. In a follow-up study by Breuillard et al. (2019) this is investigated further with one of the main results being that the waves do not vanish, instead the frequency is lowered (from $\sim 50\,\text{mHz}$ to $\sim 20\,\text{mHz}$). They conclude that this decrease is due to the additional ion-neutral friction slowing down the cometary ions and thus changing the Doppler shift of the wave frequency.

It is also found that the singing comet power is diminished in one hemisphere of the coma in the near-tail (Volwerk et al., 2018). It is speculated that this is due to the orientation of the convective electric field, which should influence the location of the generation region of the waves.

In this publication we investigate for the first time where these low-frequency waves are detected in the plasma environment especially with regards to the convective electric field direction and how their frequency evolved with time during the pre-perihelion time period of the Rosetta mission.

2 Data and Methods

We use magnetic field measurements from the Rosetta Plasma Consortium (RPC) magnetometer (MAG) (Glassmeier, Richter, et al., 2007), resampled to 1 Hz in cometocentric solar equatorial (CSEQ) coordinates. When burst mode data is available, we use a filter with a cutoff frequency of 0.9 Hz to resample to 1 Hz (to ensure suppression of all high frequency contributions), in normal mode the onboard filter is used. We use data from August 2014 to end of March 2015. This interval was chosen to cover as many gas production rates and cometocentric distances as possible, while retaining the best available data quality. The end of March cutoff was chosen because it is roughly where the solar wind ion cavity is larger than the spacecraft cometocentric distance and Rosetta is considered to be orbiting in the inner coma. This corresponds to a gas production rate of roughly $5\times10^{26}\,\text{s}^{-1}$. Only one interval has a suitable orbit to investigate the behaviour of the waves at similar gas production rates and far from the nucleus: the tail excursion in March 2016 (Volwerk et al., 2018).This interval is not included in the statistical study because the magnetic field is not as reliable due to a lack of calibration opportunities. With a more cautious approach to the magnetic field measurements, it can still be used for a case study, as was done in Volwerk et al. (2018).

We develop a new method to detect wave activity and the wave properties. We compute the power spectral density in a 600 s sliding interval with an overlap of 300 s. For the power spectral density estimator we use Welch's method with an interval length of 0.25 of the original signal length and an overlap of 0.125. From this the 95 % confidence interval is computed as well. Then a linear fit (in a double logarithmic plot) is made for all frequencies below 0.1 mHz. This cutoff frequency was chosen due to the filter cutoff

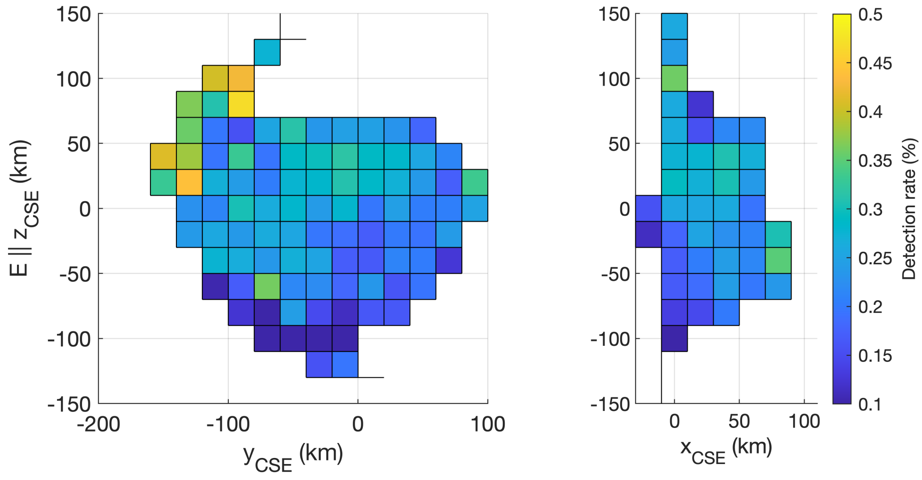

Figure 1. Distribution of the wave detections in two planes of the CSE frame. The spacecraft coverage for the same planes is shown in Fig. 2.

that is used to resample the magnetometer data onboard (normal mode). This filter cut-off makes it very difficult to correctly interpret frequencies above $\sim 200\,\mathrm{mHz}$. Then the spectrogram is detrended using the linear fit and the largest peak is determined. A positive wave detection is logged if the peak prominence is more than two times the confidence interval.

Richter et al. (2016) uses a different method to determine the properties of the singing comet waves. This method involves computing the PSD estimate in a sliding interval and then integrating in a spectral band between 10 mHz and 100 mHz. However, this method does not distinguish intervals that have a clear wave signature from intervals without one.

We use the reference frame CSE (cometocentric solar electric), in which the x-axis points toward the Sun, the z-axis points along the convective electirc field, and y completes the right handed system. Since Rosetta has no instrument to determine the convective electric field, we estimate its direction by $\vec{E} = -\vec{v} \times \vec{B}$, whereby $\vec{B}$ is the measured field. The solar wind velocity $\vec{v}$ is estimated to be 400 km/s pointing in anti-sunward direction. This is similar to the approach taken by Edberg et al. (2019). Since it is only the direction of the solar wind that is of importance for the electric field direction, variations in the speed are of minor importance. To ensure that a change in magnetic field in the 10 minute interval is not interfering with the electric field estimate, we discard intervals where more than 20% of the magnetic field vectors deviate by more than 30° from the mean field vector. These numbers represent a trade-off between retaining clear intervals and larger statistics. Note that changing them does not alter the results qualitatively.

We also use the CSEQ (cometocentric solar equatorial) system, where the x-axis points towards the Sun, the z-axis is aligned with the solar North pole and the y-axis completes the right handed system. The gas production rate is derived using the in-situ data from ROSINA-COPS (Balsiger et al., 2007) and a spherical coma model (Haser, 1957).

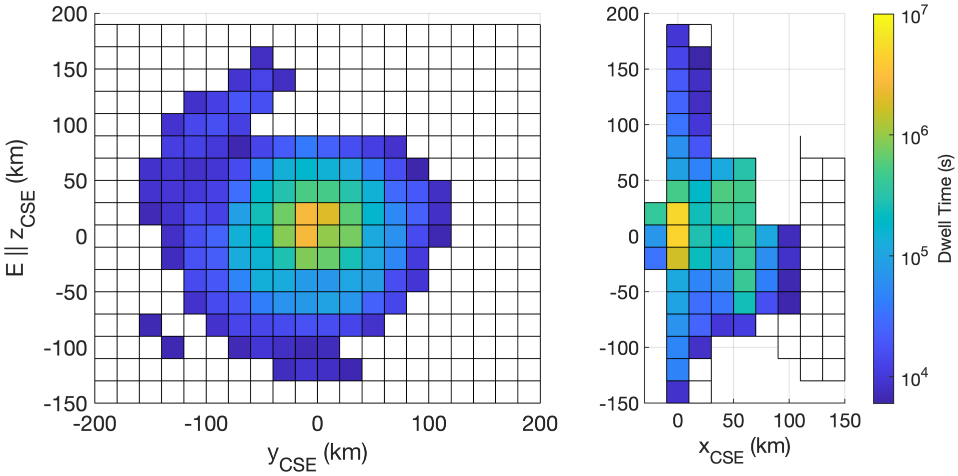

Figure 2. Spacecraft dwell time in the same coordinate system as Fig. 1. Note that the colour scale is logarithmic. White patches indicate that the dwell time is below the cut-off of 6000 s.

3 Results and Discussion

3.1 Location of the Wave Detections

The locations in the CSE frame at which waves are detected are shown in Fig. 1. The wave occurrence is normalized by the spacecraft dwell times to correct for spatial bias. Grid points with less than 100 minutes dwell time are discarded as the wave determination interval was 10 minutes with a 5 minute overlap and we require at least 20 points for the normalization. Wave occurrence is rather homogenous in the vicinity of the comet, with no specific region dominating. The total occurrence rate of the waves is 0.21 % in the $-E$ hemisphere and 0.28 % in the $+E$ hemisphere. These rates are essentially the same, therefore we conclude that there is no preferred hemisphere for wave detection. We have also performed the same analysis in the CSEQ system with similar results (not shown). This does not agree with the simulations by Koenders et al. (2016), where the waves were only seen in the $+E$-hemisphere.

We present two possible explanations for this discrepancy. First, our findings could indicate that the cross-field current is not part of the generation mechanism. Or second, the coherence length and the source region are much larger than the cometocentric distance that Rosetta covers ($150 - 200$ km). This means that Rosetta is not able to see any asymmetry with respect to the convective electric field. However, Richter et al. (2016) estimate a coherence length of ~ 50 km and a source region size of up to 100 km, which means that the source region size would be smaller than the covered distance and we therefore should see a difference between the two E hemispheres.

3.2 Wave Power and Frequency Distribution

Fig. 4 shows the time evolution of the frequency as well as the gas production rate and the spacecraft position. The spatial distribution of the wave power was investigated by Richter et al. (2015). We can affirm their finding that the peak PSD increases as the cometocentric distance decreases (see panel 2, 4, 5 of Fig. 4) and that there is no correlation between the PSD and the magnetic field magnitude. This is true for both detection methods.

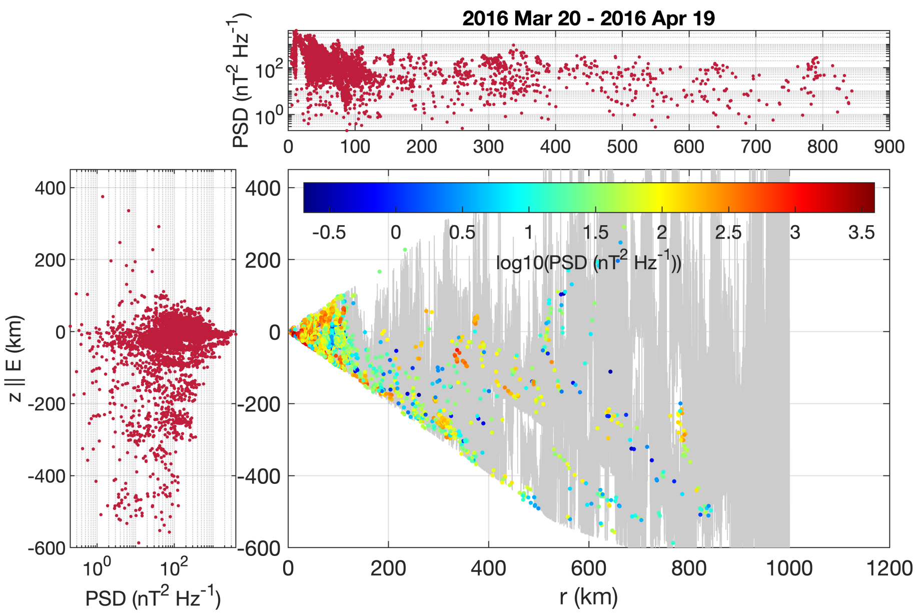

Figure 3. Peak wave power spectral density in a cometocentric distance - z_{CSE} plot. The power spectral density is color coded and each point corresponds to one 10 minute interval. The grey line follows the position of the spacecraft. The smaller figures to the top and left show the power spectral density over r and z.

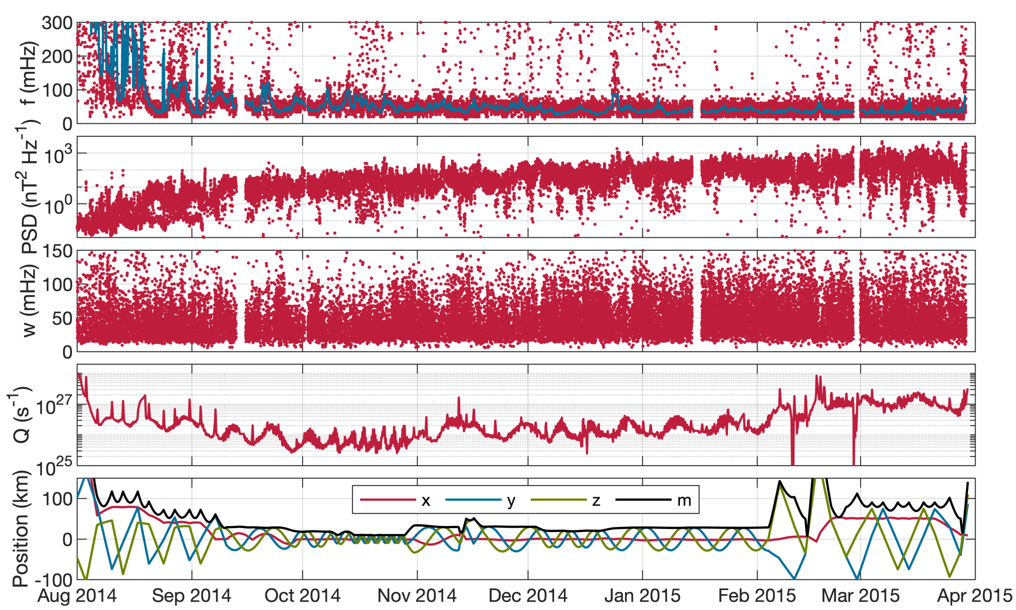

Figure 4. From top to bottom: peak frequency (with moving mean in blue), peak power spectral density, width (w) of the peak, gas production rate estimate, and spacecraft position in CSEQ. For better visibility, the gas production rate was treated with a moving average over 10000 data points.

The frequency does not depend on the cometocentric distance or the magnetic field magnitude. The frequency is clearly changing (uppermost panel), from values above 90 mHz up until early October to values below 90 mHz afterwards. There is also a distinct oscillating pattern in the higher frequency regime.

We have performed a correlation analysis between the frequency and plasma density, neutral density, Alfvén velocity, and gas production rate derived from a simple, spherical model (Haser, 1957) and observations, gas production rate from an empirical model (Hansen et al., 2016), spacecraft position in CSEQ, CSE and a comet fixed frame. There are no clear correlations found, except that the position of the spacecraft in z direction in CSEQ shows a remarkable similarity. Fig. 5 shows this more clearly. For values of z_{CSEQ} greater than 20 km the frequency increases by a factor of three, compared to other values. We have ruled out that this is due to the radial distance, or due to the longitude and latitude of Rosetta in the comet-fixed system.

Meier et al. (2016) show that the phase structure caused by the ion-Weibel instability is highly asymmetric along z in the CSEQ system (referred to as cometary frame of reference in the publication). This is due to the Doppler shift when transforming from a current-aligned to a stationary coordinate system. This asymmetry could explain our findings here. However, it is unclear why this asymmetry is not visible in the CSE frame of reference, as in the theoretical model the z axis is aligned with the electric field. There are also other discrepancies between the model and the findings from the data: for example the model predicts a very steep increase of the frequency with an increase in the magnetic field strength. For a magnetic field greater than 15 nT, the frequency is modeled to be higher than 2 Hz, which is in direct contradiction to the data, where the frequency overall decreases with higher magnetic fields. However, many parameters change at the same time during the Rosetta observation period and thus the interplay of an increase in solar wind speed, magnetic field pile-up and increase in cometary ion density makes it very difficult to disentangle the contributions.

Contrary to what Breuillard et al. (2019) find, there is no correlation between the frequency and the plasma density. In fact a closer examination of the plasma density and frequency reveals intervals where they correlate, intervals where they anti-correlate, and intervals where they are 90° out of phase, shedding doubt on the correlation between frequency and density found by Breuillard et al. (2019). If they were correlated, a periodicity in the wave frequency of 6 or 12 hours according to the neutral gas density variation (Goetz et al., 2017) should also be visible, which it is not. However, it should be noted here that there is still a possibility that the wave frequency is correlated to the density in the wave generation region, which as noted above may be much larger than the distances covered by the in-situ measurements.

For the interval used in this study, Mars was located conveniently close to the Sun-comet line. The distance between Mars and the comet was approximately 1.8 AU. At a solar wind velocity of 350 km/s to 400 km/s the delay time between Mars solar wind observations and solar wind at the comet is around $8 - 9$ days. Unfortunately MAVEN observations at Mars only start in October 2014, and Mars Express has no magnetic field instrument. However, we can compare the Mars Express ASPERA-3 IMA proton moments with the observed frequency development. There is no obvious correlation, especially considering the uncertainty in the solar wind propagation. Earth was in a disadvantageous position compared to the comet, so propagation models are not optimal. No obvious correlation can be found with solar wind parameters propagated from Earth (Tao et al., 2005).

The width of the peak also does not correlate clearly with any of the investigated parameters. One could, maybe infer from Fig. 4 that the width slightly increases with gas production rate. One possible explanation could be that the density in the wave generation region, or the size of the wave generation region itself modify the frequency and

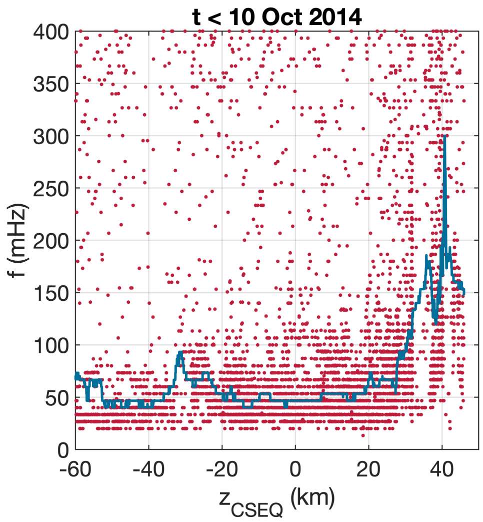

Figure 5. Frequency of the wave over the z-coordinate in the CSEQ system. The blue line shows a moving average.

during the higher activity times waves are generated at more frequencies increasing the width of the peak.

4 Conclusions

We have performed a study of the properties of low-frequency waves in the plasma environment of comet 67P. A new method allows for the distinction of intervals where the waves are present and intervals where they are not observable. We find that:

- waves occur everywhere in the cometary environment, regardless of electric field direction.
- the wave generation region can tentatively be constrained to $> 800\,\mathrm{km}$.
- the wave frequency changes from $> 90\,\mathrm{mHz}$ at large heliocentric distances to $< 90\,\mathrm{mHz}$ at smaller heliocentric distances.
- the wave frequency is not a function of the plasma density.
- the wave frequency during the earliest stages of cometary activity depends on the spacecraft position in CSEQ.
- the wave width changes from low at large heliocentric distances to high at small heliocentric distances.

Thus we found that the wave generation region is larger than previously estimated and that the in-situ plasma density is not the driver of the wave frequency. To constrain this further measurements with two spacecraft and/or more statistics are necessary.

The findings are partly in agreement with the predictions for a modified ion-Weibel instability, however they disagree with the hybrid simulations which predicted an asymmetry in the wave occurrence along the convective electric field direction.

Acknowledgments

Datasets of the RPC-MAG, RPC-LAP and ROSINA instruments onboard Rosetta as well as the dataset of the ASPERA-3 instrument onboard Mars Express are available at the ESA Planetary Science Archive (Besse et al., 2018, http://archives.esac.esa.int/psa). CG is supported by an ESA Research Fellowship.

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Supporting Information for "Singing comet waves in a solar wind convective electric field frame"

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Contents of this file

Text S1. We verify the peak detection method by examining randomly selected 10-minute intervals and one interval in the pure solar wind. As required, the method does not detect a wave signal in the solar wind (upper panel, Fig. S1), but it does detect the clear wave signal in the coma (lower panel of the same figure). Examination of a number of randomly selected intervals shows good agreement between automatic and manual selection of wave frequency, power and existence.

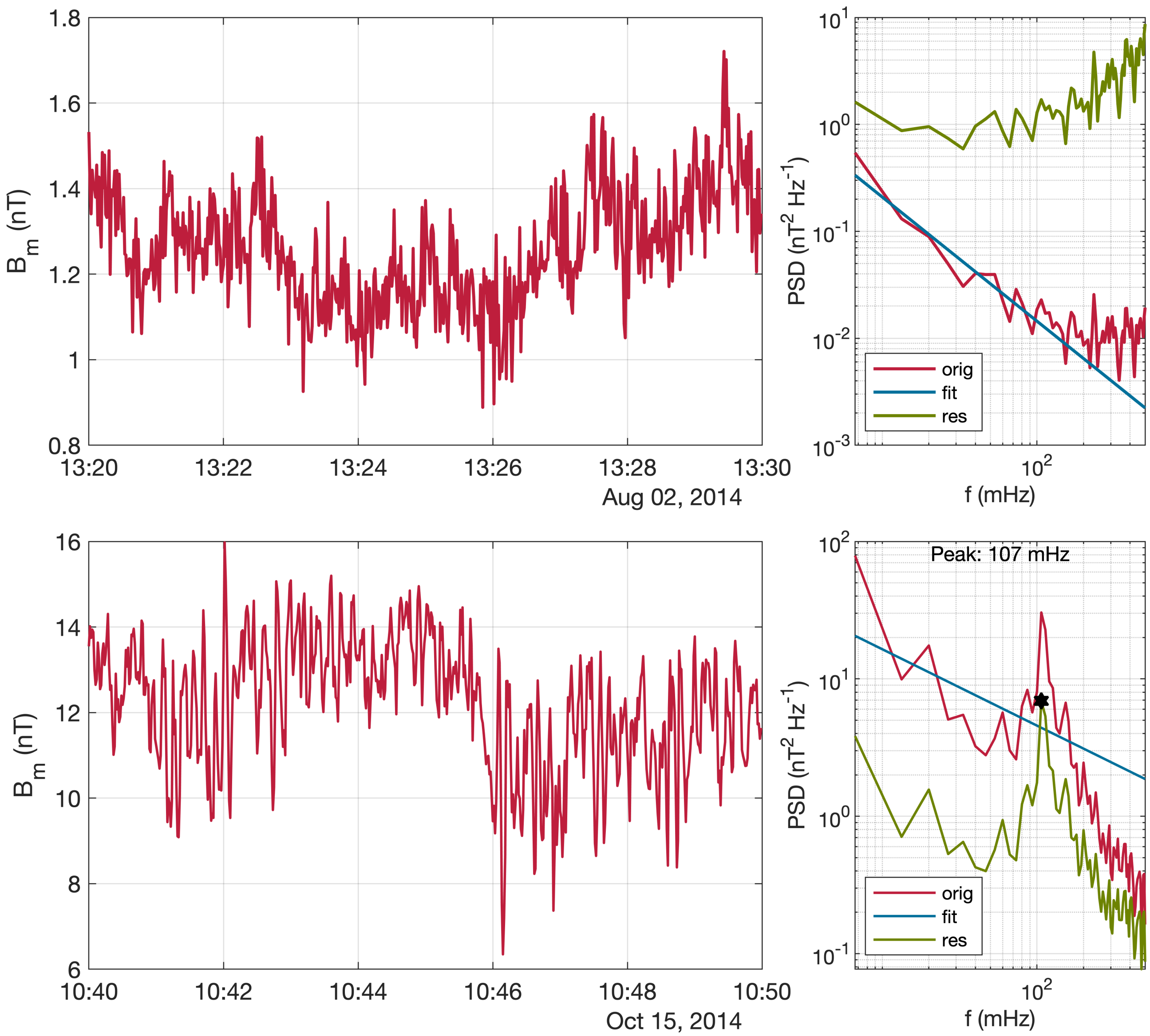

Figure S1. Left: Magnetic field magnitude for two 10-minute intervals. Right: Power spectral density estimate of the original time series (orig), linear fit (fit) and resulting normalized PSD (res). If a wave is detected the peak is marked by a star and the frequency is stated in the plot.