Dataset Overview

This bundle consists of ASCII formatted plasma wave frequency and derived electron plasma density data as measured by the Waves instrument on Juno and calculated from the equations of cold plasma theory.

These are digitized frequencies of characteristic frequencies found in Juno wave spectra that are dependent on the electron plasma frequency, hence, yield the electron density. The data were taken from Juno wave spectra obtained during its orbital mission at Jupiter. The data include select measurements from spacecraft event time (SCET) 2016-07-05T00:00:00.000Z to 2025-09-30T00:00:00.000Z. The data are separated into files by time (e.g. by day and hour of day) and the individual data points are typically taken every 1-second when a relevant resonant or cutoff frequency can be identified. As will be explained in more detail below, the density measurements in this data set are measured from Juno plasma wave spectra. Usually, these spectra are computed from Juno burst mode waveforms, but can, in principle, be derived from lower spectral resolution survey spectra.

Density datasets are by target data collections.
Specific datasets were created for research purposes and at least two are in published scientific papers. Published papers are located in the document collection of this bundle and are referenced below. It is anticipated that these collections will grow as additional densities are determined and published in the refereed literature.

The Waves instrument is described in WAVESINST.CAT at
https://doi.org/10.17189/1520498 and also in
Kurth, W. S., G. B. Hospodarsky, D. L. Kirchner, B. T. Mokryzcki, T. F. Averkamp, W. T. Robison, C. W. Piker, M. Sampl, and P. Zarka The Juno Waves Investigation Space Sci. Rev., 213(1), 347-392, doi:10.1007/s11214-017-0396-y, July 10, 2017.
The Juno spacecraft is described in INSTHOST.CAT at
https://doi.org/10.17189/1520498.
The Juno mission is described in MISSION.CAT at https://doi.org/10.17189/1520498.

Waves burst data: https://doi.org/10.17189/1522461
Waves survey data: https://doi.org/10.17189/1520498
Juno Magnetometer: https://doi.org/10.17189/1519711

Bundle Citation:
Kurth, W. S., Elliott, S. S., Sulaiman, A. H., Wilkinson, D. R., Faden, J. B., Piker, C. W. juno-waves-electron-density-V1.0, Juno Waves Electron Density 1S V1.0, NASA Planetary Data System, 2024.

Published papers referenced in this bundle:

Elliott, S. S., Sulaiman, A. H., Kurth, W. S., Faden, J., Allegrini, F., Valek, P., et al. (2021). The high-latitude extension of Jupiter's Io torus: Electron densities measured by Juno Waves. Journal of Geophysical Research: Space Physics, 126, e2021JA029195.
https://doi.org/10.1029/2021JA029195

Sulaiman, A. H., Elliott, S. S., Kurth, W. S., Faden, J. B., Hospodarsky, G. B., & Menietti, J. D. (2021). Inferring Jovian electron densities using plasma wave spectra obtained by the Juno/Waves instrument. Journal of Geophysical Research: Space Physics, 126, e2021JA029263.
https://doi.org/10.1029/2021JA029263

Sulaiman, A. H., Mauk, B. H., Szalay, J. R., Allegrini, F., Clark, G., Gladstone,

G. R., et al. (2022). Jupiter's low-altitude auroral zones: Fields, particles, plasma waves, and density depletions. Journal of Geophysical Research: Space Physics, 127, e2022JA030334. https://doi.org/10.1029/2022JA030334

Kurth, W. S., Sulaiman, A. H., Hospodarsky, G. B., Menietti, J. D., Mauk,B. H., Clark, G., et al. (2022). Juno plasma wave observations at Ganymede. Geophysical Research Letters, 49, e2022GL098591. https://doi.org/10.1029/2022GL098591

Kurth, W. S., Wilkinson, D. R., Hospodarsky, G. B., Santolik, O., Averkamp, T. F., Sulaiman, A. H., et al. (2023). Juno plasma wave observations at Europa. Geophysical Research Letters, 50, e2023GL105775. https://doi.org/10.1029/2023GL105775

Connerney, J. E. P., Kotsiaros, S.,Oliversen, R. J., Espley, J. R., Joergensen,J. L., Joergensen, P. S., et al. (2018). A new model of Jupiter's magnetic field from Juno's first nine orbits. Geophysical Research Letters, 45, 2590-2596. https://doi.org/10.1002/2018GL077312

Connerney, J.E.P., Timmins, S., Herceg, M., & Joergensen, J. L. (2020). A Jovian magnetodisc model for the Juno era. Journal of Geophysical Research: Space Physics, 125, e2020JA028138. https://doi.org/10.1029/2020JA028138

Parameters
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While the data essential to this bundle are the electron plasma densities, there are a number of characteristic frequencies of the magnetized plasma included with this data. The data consist of ASCII files with one record per time step, occurring in 1-second increments, although there may not be a record for every time step, depending on instrument mode and the availability of interpretable spectral features. Each record includes the time, magnetic field strength (obtained from the Juno magnetometer), the electron cyclotron frequency (if magnetometer data are available), the frequency of the cutoff or resonance measured, a code indicating the name of the frequency measured, the calculated electron density, and a set of position coordinates for the spacecraft at the time of the observation.

Also included in each record are the electron plasma frequency(fpe), extraordinary mode cutoff frequency(fR=0), ordinary mode cutoff frequency(fL=0), upper hybrid resonance frequency(fuh), and a quality index. One of these four frequencies is just a copy of the measured cutoff or resonance frequency while the remaining frequencies are calculated using the magnetic field data and the equations of cold plasma theory. Different files are used for each day.

Processing
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The ASCII density data files produced in this bundle were derived from measuring the characteristic frequencies from the local plasma. The density was calculated from these data, along with cyclotron frequency data derived from magnetic field data, using the equations of cold plasma theory.

In order to measure these characteristic frequencies, this work utilizes an Autoplot (www.autoplot.org) script that allows the operator to highlight the general vicinity of the cutoff or resonance on a frequency-time spectrogram. Then, an algorithm finds the cutoff or resonance in the region and records the frequency at 1 second intervals. Hence, the automated procedure has a high temporal resolution (1 second) and requires a relatively low level of both manual effort and subjective judgment by the operator. While the operator utilizes a color or gray-scale spectrogram to guide the cutoff and peak detectors, we emphasize that this is only used as a means of identifying the appropriate range in frequency for the algorithm to search. The algorithm utilizes the spectrum and does not depend on a color scale to determine the characteristic frequencies. This should reduce systematic error and lead to more accurate results. The autoplot script also allows the operator to manually specify a particular frequency should the algorithm find the feature too weak or diffuse to determine automatically.

Data Coverage
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This bundle does not provide complete coverage of Juno's orbital mission in Jupiter's magnetosphere. In fact, the initial dataset only contains data from high-latitude passes through the extension of Io's plasma torus through Perijove 29 as described in Elliott et al. (2021). The Elliott et al. (2021) data only include times for which there are burst waveform measurements. It is anticipated that additional data will be added to this data set upon the completion of additional studies that result in the determination of electron densities in a similar manner. There is no plan to provide a complete dataset covering the entire Juno mission because spectral features that could yield a determination of the electron density are not always present.

Interpretations
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High resolution wideband waveform data were used to measure characteristic frequencies (peaks and cutoffs) which relate to the electron plasma density. When dealing with a variety of spectrograms and plasma conditions found in different regions of the Jovian magnetosphere, it is necessary to interpret the present modes and characteristic frequencies correctly in order to determine the most accurate value for the electron plasma density. This is a very simplified discussion of the techniques used to derive electron densities in this bundle and the user is strongly encouraged to read Sulaiman et al. (2021) and Elliott et al. (2021) for important details.

The simplest frequency to consider is fpe, the electron plasma frequency because it is directly related to electron density for a cold plasma by

fpe [Hz] = 8980(n e[cm -3]) 1/2 .

When fpe > fce then fuh^2 = (fce^2 + fpe^2) can be used with

fce [Hz] (= 28B [nT])

to compute fpe. For this data set, we rely on the identification of one or more characteristic frequencies of a magnetized plasma including:

1. fpe from the upper cutoff of whistler mode emissions
2. flh from the lower cutoff of whistler mode emissions
3. fpe from the frequency of plasma oscillations
4. fuh from the frequency of a special instance of electron cyclotron emissions where fuh is between harmonics of fce.
5. fL=0 from the low-frequency cutoff of z-mode emissions
6. fR=0 from the low-frequency cutoff of right-hand extraordinary mode emissions

From one of these:

N_e (electron plasma density)

is calculated.

Note that for the very strong magnetic fields near Jupiter, fuh is not useful in the inner magnetosphere because when fce >> fpe, fuh and fce are essentially identical and provide no useful information on fpe, hence, electron density. However fuh can often be detected in the middle and outer magnetosphere where fpe > fce, hence, is useful in these regions. Further, common approximations used in computing the hybrid frequencies are not appropriate close to Jupiter for the same reason, hence, the datasets utilize numerical solutions for the hybrid frequencies.

The methods used for interpreting different spectra are described in Elliott et al. (2021) and Sulaiman et al. (2021). Sometimes, more mode cutoff is present at different frequencies for the same time is the case, we can use multiple spectral features to compute the compare in detail in than one wave period. When this density and for consistency. Or, more directly, we can use the identification of one characteristic frequency to compute another and determine whether they agree. A consistent interpretation is one where the calculated frequencies match the cutoffs/peaks present in the spectrum. If so, confidence in the identification(s) is increased.

Ancillary Data
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Each row in the data includes various ephemeris parameters describing the location of Juno for that time. These are based on the most recent SPICE SPK kernels available at the time the file is created. For all data in the bundle, Jupiter-centered coordinates are included. For densities determined in the vicinity of one of the Galilean satellites, which may be available for a small number of flybys, ephemeris information centered on the relevant satellite are also included.

Coordinate System
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Included in the data are ephemeris information that give an accurate location of Juno at the time the density data points were determined. The coordinates consist of altitude, distance, longitude and magnetic latitude and is referred to commonly as the Jovicentric coordinate system, or one that is fixed to the rotation of the planet.

We have used the System III coordinate system which uses the planet's magnetic field to measure the rotation. The radial distance is defined as the distance from the center of Jupiter to the spacecraft (in kilometers) divided by the radius of Jupiter at the equator (71492 km). In the usual astronomical convention, the longitude is a west longitude which increases with time from an observer above the system, rather than just the angle of rotation about the z-axis. Also included is Juno's M-shell at the time of the measurement. This is similar to the L parameter for a dipole field, but uses a Juno-determined internal field model and model for the current sheet. The model used for this bundle is JRM09+CS (see Connerney et al. (2018) and Connerney et al. (2020)). Altitude above the 1-bar level using the IAU ellipsoid describing Jupiter is also given.

Software
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The software used to generate this data set is based on autoplot (www.autoplot.org) and uses a script found at
https://research-git.uiowa.edu/abbith/juno/-/blob/main/team/digitizer/addPointDigitizer.jy

Confidence Level
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Densities are provided where Juno Waves data exist and where a confident determination of a relevant characteristic frequency can be determined. Since burst waveform data provide superior spectral resolution, hence, density resolution, most of the data in the inner and middle magnetosphere utilize burst data. Given a correct interpretation of the characteristic frequency, the primary sources of error are:

1. The spectral resolution of the instrument. For waveforms from the low frequency receiver, low band, this is approximately 10 Hz. For the high band of the low frequency receiver, this is approximately 75 Hz. In the case wheresurvey data are used, the spectral resolution is ~25%. Percentage errors in frequency are multiplied by two for the purposes of determining density resolution.

2. Where a cutoff is used to determine a characteristic frequency, the steepness of the cutoff in frequency space can affect the error in density determination. A gradual slope will have more error than a sharp cutoff.

3. In computing the characteristic frequencies we have assumed an electron-proton plasma. The introduction of heavier ions will change the hybrid frequencies. At higher latitudes where the heavier ions are less populous, this should introduce negligible errors. In the plasma sheet and Io torus, the hybrid frequencies may be significantly affected.

Limitations
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The uncertainty in fpe translates into a variable uncertainty in the plasma density and is greater in a relative sense when the plasma frequency is low. For example, if we assume an error of 100 Hz in any measurement, a measurement at 300 Hz produces a 70% fractional uncertainty in the density. However, if the measurement is made at 3 kHz, then the fractional uncertainty of the density is much smaller, approximately 7%. It is important to note that if the plasma frequency is not present in the spectrum, the electron plasma density must be calculated using another characteristic frequency and the cyclotron frequency, which is directly proportional to the local magnetic field. If magnetic field data do not exist for a region where the plasma frequency cannot be measured directly, the density cannot be determined.

The initial dataset focuses only on the high-latitude extension of the Io torus. In the future, we expect to be able to include densities from the outer magnetosphere using the low-frequency cutoff of continuum radiation. Burst data are very sparse in the outer magnetosphere, so survey data would be necessary and would yield poorer accuracies. We also expect to be able to determine electron densities in and near the ionosphere. These additional measurements are the subject of ongoing studies and will be archived upon publication of those studies.

Targets
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Jupiter (for most measurements in this data set)
Ganymede (for the orbit 34 flyby)
Europa (for the orbit 45 flyby)
Io (for the orbit 57 and/or 58 flybys)