ANALYSIS OF VARIATIONS IN THE IO PLASMA TORUS USING GALILEO PLS DATA

Scott Siler
Summer 2013 REU Solar and Space Physics program
MOP group with Fran Bagenal, Rob Wilson, et. al.
University of Colorado at Boulder
Laboratory for Atmospheric and Space Physics
What’s all this then?

• We all know Jupiter’s pretty awesome, but how awesome???? Can learn a lot with ground observations, but nothing beats in-situ data

• Two primary things to investigate: temporal variation and local time variation
Why do we care?

- Gives us insight about magnetospheres in general
- Very limited data set on extraterrestrial systems, especially over the long term
- Much left to be understood about physics behind mass loading of Jupiter’s inner magnetosphere by ions from Io’s volcanoes
## Why do we care?

### Spacecraft (within 200 R\textsubscript{J})

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Encounter Date/C.A.</th>
<th>Closest R (R\textsubscript{J})</th>
<th>Type</th>
<th>Spin</th>
<th>Energy Range (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pioneer 10</td>
<td>1973-Dec-04</td>
<td>2.9</td>
<td>Fly-by</td>
<td>Yes</td>
<td>100 – 4,800</td>
</tr>
<tr>
<td>Pioneer 11</td>
<td>1974-Dec-03</td>
<td>1.7</td>
<td>Fly-by</td>
<td>Yes</td>
<td>100 – 4,800</td>
</tr>
<tr>
<td>Voyager 1</td>
<td>1979-Mar-05</td>
<td>4.9</td>
<td>Fly-by</td>
<td>No</td>
<td>10 – 5,920</td>
</tr>
<tr>
<td>Voyager 2</td>
<td>1979-Jul-09</td>
<td>10.1</td>
<td>Fly-by</td>
<td>No</td>
<td>10 – 5,920</td>
</tr>
<tr>
<td>Ulysses</td>
<td>1992-Feb-08</td>
<td>6.3</td>
<td>Fly-by</td>
<td>Yes</td>
<td>255 – 34,400</td>
</tr>
<tr>
<td>Galileo</td>
<td>1995-Nov-10 to 2003-Sep-30</td>
<td>0 Perijoves: 5.5-9.5</td>
<td>Orbiter (Equatorial)</td>
<td>Yes (Spin Platform)</td>
<td>0.9 – 53,000</td>
</tr>
<tr>
<td>Cassini</td>
<td>2000-Dec-30</td>
<td>137</td>
<td>Fly-by</td>
<td>No, but has actuator</td>
<td>1 – 50,280</td>
</tr>
<tr>
<td>New Horizons</td>
<td>2007-Feb-28</td>
<td>32.2</td>
<td>Fly-by</td>
<td>No (fly-by) (Yes &gt; 300R\textsubscript{J})</td>
<td>35 – 7,500</td>
</tr>
<tr>
<td>Juno</td>
<td>~2016-2017</td>
<td>1.06</td>
<td>Orbiter (Polar)</td>
<td>Yes</td>
<td>10 – 40,000</td>
</tr>
</tbody>
</table>
Why do we care?
What are we looking at?

- Focused on a nested set of 3 quarter-spherical plate electrostatic analyzers
What are we looking at?

- ESA gives energy resolution. Imagine ions as basketballs that you give just enough energy for gravity to sink the shot.
- Spacing of 7 anodes in a fan-shape on the side gives 3-D spatial resolution.
What are we looking at?

Galileo PLS Energy steps and Coverage

**SKIPPED STEPPING DUE TO ANTENNA ISSUE**

To measure photo-electrons
What are we looking at?

• 4 (low/mid) or 8 (high) sweeps in a spin
• Counts accumulated over time (determined by resolution setting)
• Accumulated sweeps over one spin are “merged”
• Our available data set: 114133 total merged spins
Galileo Merging of Data Spins

How data is taken on Galileo

Note different data spins start at different phases.

Data after merging and realigning spin phases.

Quality spectra, both in energy and all sky!
How are we analyzing the data?

- Expect the plasma to be in thermal equilibrium, follows a convective Maxwellian velocity distribution
- Predicted number of counts given by:
  \[ C = dt \times GF \times v^4 \times f(v) \]
  - Adjustable parameters are \( n, T, V_0 \) (3 components)
Fitting

• (Careful) chi-squared minimization allows us to eek out best fit parameter values
• Errors on parameters are essentially the width of the hyperdimensional chi-squared well

\[ \chi^2 = \frac{1}{v} \sum \frac{(y_f - y_i)^2}{\sigma_i^2} = \frac{1}{v} \chi^2 \]
Getting started

Counts in anode1 vs. Energy; considering species S+ and O+

Red = data
Green = total flux; minimum chi-squared: 32.95
--- bulk speed [m/s]: 3.74E+04 (+-) 2.51E+02
Blue = O+ flux
--- number density [m^-3]: 2.35E+08 (+-) 7.80E+06
--- thermal speed [m/s]: 2.15E+04 (+-) 2.36E+02
Purple = S+ flux
--- number density [m^-3]: 4.06E+08 (+-) 9.85E+06
--- thermal speed [m/s]: 2.47E+04 (+-) 1.35E+02
Better Fitting

• Employed a more complex iterative chi-squared minimization routine using Differential Evolution to find vicinity of global min in parameter space

• Simplex uses that to rapidly identify minimum
Assumptions

- Isotropic (data too sparse for anisotropic)
- Several species present (S ++, O+, SO++, ... ions), but peaks overlap too much to distinguish $\Rightarrow 32 \text{ amu/2e} = 16 \text{ amu/1e}$
- From recent Cassini UV observations [Delamere and Bagenal, 2005], we used relative abundances of species to get an average mass-to-charge (actually variable m:q with respect to radial distance)
Higher frequency pattern: energy bin sweep

Lower frequency pattern: spacecraft spin

X-axis: daisy chained energy bin steps
Discovered difficulties

- At first, churned out the fits and plotted those with sufficiently low error to value ratio
- Gave too much scatter to have any confidence in the radial profiles
Why so much scatter?

Vast majority of records too noisy or featureless to fit properly, (partly due to flooding of detectors by energetic radiation belt particles)
How to proceed with messy data

• Can’t afford to throw out points unless absolutely necessary

• Went back and looked at several individual records at various times, distances, etc. to develop more rigorous selection criteria based on observed patterns

• Examples: one-sided peaks, false peaks, background noise levels, missing anode data, etc.
“Pruning?”

• Introduced harder eligibility conditions for fitting (e.g. max counts > 10, only consider peak anodes and its neighbors, etc.)
• Gave us nearly 4 times more successfully fit merged spins
  ▪ Dramatically reduced the number of null points being fitted, more realistic errors
Looking better!

Pruned data (1999)
Red = low-resolution, Yellow = mid, Green = high

Raw data (1999)
Red = low-resolution, Yellow = mid, Green = high
Binning

- Being satisfied with the points that made it through the pruning, we can get a smoother feel for the data by binning points by radial distance.
- Different bin sizes at radii regimes to compensate for different conditions (.25Rj, .5Rj, 1Rj)
Gold = noon
Black = midnight
Red = dawn
Blue = dusk
Green =
--Corotation
(rigidly rotating with Jupiter)(v\phi)
--Fran Bagenal’s
derived density profile[2004] (n)

NOTE THE
DIMINUITIVE ERROR
BARS!!!!!
What are we to make of this?

• Difficult to take such small errors seriously
• Thought perhaps it’s the way we’re binning the points; been using the weighted average of the sample
• Found several different ways to calculate error on this average; made plots to understand relative size of these errors
\[
\sigma_v^2 = \frac{1}{N-1} \sum \frac{(x_i - \bar{x})^2}{\sigma_i^2} \quad \text{(red)}
\]

\[
\sigma_q^2 = \sum \sigma_i^2 \quad \text{(blue)} \quad \text{error}
\]

\[
\sigma_{m}^2 = \frac{\sum \sigma_i^2}{N} \quad \text{(yellow)}
\]

\[
\sigma_s^2 = \frac{1}{N-1} \sum (x_i - \bar{x})^2 \quad \text{(purple)}
\]

\[
\sigma_{r\theta}^2 = \sum \left(\frac{1}{\sigma_i^2}\right) \quad \text{(green)}
\]

\[
\sigma_{\rho M} = \langle x^2 \rangle - \langle x \rangle^2 \quad \text{(turquoise)}
\]
Conclusions from error analysis

- Weighted mean skews too far to points with small errors; while this is usually desired, with such sparse data, this usually indicates poor fits.
- Too many different ways to calculate errors, none of which we can be very confident.
Changing it up a bit

• It seems better, at least when dealing with Galileo data, to bin the points by the MEDIAN, not the mean. (Think about house prices)

• First and third quartiles are able to show asymmetry in the distribution of points, information that averaging might have blurred out
Pruned binned fits from 1995 to 2003

Best fit: $66.512 \times (\text{SC}_R / 6)^{0.95}$

Best fit: $127.353 \times (\text{SC}_R / 6)^{1.74}$

Best fit: $492.095 \times (\text{SC}_R / 6)^{-6.296}$

Radial distance from Jovian center [$R_J$]
Well that’s nice and all, but is there maybe a better way to visualize the data???
On no!! We’re going 2D!!!

• Galileo only remained within $15^\circ$ of equator
• HOWEVER:
  Rotation $\rightarrow$ Centrifugal force $\rightarrow$ Gaussian distribution with peak at equator [Hill and Michel, 1976]
• $N(z) = n_0 \times \exp(-(z/H)^2$, where $H$ essentially only depends on temperature
• Allows us to extrapolate a rough meridional profile from an equatorial profile!
Results thus far

• Established pruning process that efficiently weeds out unwanted data points
• See peak in density at ~6 Rj from Io mass loading, then follows radial behavior of Fran’s profile, but values are slightly lower
• Seeing subcorotation (~80%)
• Still unclear about presence of significant local time dependence, but initial meridional profiles possibly hinting at something interesting in dusk/midnight sectors; need to better understand possible sources of errors here
Further studies

• Further investigate data for local time/long-term temporal variations
• Compare profiles with theories of mass transport
• See if results from PLS data can be reconciled with results from EPD data/numerical moments
Acknowledgements

• Fran Bagenal and Rob Wilson for their infinite patience and wisdom
• Laila Andersson for giving me the chance to make a plasma 😊
• Everyone at LASP for their assistance whenever I came in to bug them
• The NSF, Marty, Erin and everyone in this REU for making this summer far better than I could have imagined
• Marc the coffee guy for the constant spirit boosts