

Summary of Analysis to Date of Voyager PLS Data at Jupiter,
Particularly the Io Plasma Torus

Pre-Voyager – The IPT was detected via ground-based optical emissions of neutral Na atoms and S⁺ ions in the vicinity of Io. The Pioneer spacecraft flew by Jupiter in the same timeframe but the instrument did not detect the heavy ions from Io. Intriligator re-evaluated the Pioneer data but it is not clear whether it is worth looking at these again.

Voyager – The UVS instrument detected strong emissions from various Sⁿ⁺ and Oⁿ⁺ ions from the Io plasma torus on approach to Jupiter. The PLS instrument detected resolved spectra occasionally in the plasmashet (10-30 RJ) and inside 5.6RJ but in the main, dense region of the torus the different ion species were not resolved.

Ralph McNutt's thesis work was on the plasma sheet:

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 86, NO. A10, PAGES 8319–8342, SEPTEMBER 30, 1981

Positive Ion Observations in the Middle Magnetosphere of Jupiter

R. L. MCNUTT, JR., J. W. BELCHER, AND H. S. BRIDGE

while my thesis work was on the Io plasma torus:

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 86, NO. A10, PAGES 8447–8466, SEPTEMBER 30, 1981

Direct Plasma Measurements in the Io Torus and Inner Magnetosphere of Jupiter

FRAN BAGENAL AND JAMES D. SULLIVAN

This shows that we had little clue about the composition – and no idea about realistic velocity distributions – so we explored 2 options: all ions having the same temperature or all ions having the same thermal speed (e.g. as if they had been picked up at the same speed). More about this later....

Around this time we also found out that the code I had inherited from Jim Sullivan was defining thermal speed as $\sqrt{kT/m}$ while my translation from thermal speed to temperature assumed thermal speed to be defined as $\sqrt{2kT/m}$. This resulted in a factor of 2 error in the earlier published temperatures:

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. A2, PAGES 1755–1757, FEBRUARY 1, 1985

Revised Ion Temperatures for Voyager Plasma Measurements in the Io Plasma Torus

FRAN BAGENAL,¹ RALPH L. MCNUTT, JR., JOHN W. BELCHER, HERBERT S. BRIDGE, AND JAMES D. SULLIVAN²

Inside 5.6 RJ the plasma got a lot colder and we could resolve composition – but this really is the back-water of the magnetosphere – most of the plasma moves outwards from Io:

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. A1, PAGES 311–324, JANUARY 1, 1985

PLASMA CONDITIONS INSIDE IO'S ORBIT: VOYAGER MEASUREMENTS

Fran Bagenal

We then got distracted by Saturn, Uranus, Neptune and not much happened with the Jupiter data. In 1994 I put together an empirical model of the torus based on Voyager PLS ion & electron data plus UVS observations of composition:

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. A6, PAGES 11,043–11,062, JUNE 1, 1994

**Empirical model of the Io plasma torus:
Voyager measurements**

Fran Bagenal

The Galileo spacecraft arrived at Jupiter in December 1995 and went into orbit. Frank Crary and I worked with Lou Frank and Bill Peterson (as best we could) to analyze the Galileo PLS data from the early orbits:

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. A12, PAGES 29,359–29,370, DECEMBER 1, 1998

**Galileo plasma spectrometer measurements
of composition and temperature
in the Io plasma torus**

F. J. Crary and F. Bagenal

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L. A. Frank and W. R. Paterson

It was clear that the Galileo data were not easy to work with – mainly because the broken antenna meant that the data were heavily decimated. There are several papers on the Io interaction and on the magnetospheric conditions by Frank & Paterson.

With Cassini flying past Jupiter on its way to Saturn in 2000, and carrying the Colorado UVIS instrument, my attention turned to torus conditions derived from spectroscopy. Andrew Steffl's PhD thesis work involved studying the temporal and spatial distribution of ions in the torus based on careful analysis of the UVIS spectra as well as physical chemistry models of the Io plasma:

- Cassini UVIS observations of the Io plasma torus. I. Initial results, Andrew J. Steffl, A. Ian F. Stewart and Fran Bagenal, *Icarus*, 172, 78-90, 2004
- Cassini UVIS Observations of the Io Plasma Torus: II. Radial Variations, Andrew J. Steffl, Fran Bagenal, A. Ian F. Stewart, *Icarus*, 172, 91-103, 2004
- Cassini UVIS observations of the Io plasma torus III: Temporal and Azimuthal Variability, Steffl, A., Delamere, P., Bagenal, F., *Icarus*, 180, p124-140, 2006
- Cassini UVIS Observations of the Io Plasma Torus. IV. Modeling Temporal and Azimuthal Variability, A. J. Steffl, P. A. Delamere, F. Bagenal, *Icarus*, 194, 153-165, 2008

The physical chemistry model was developed by Peter Delamere and later adapted by Andrew Steffl for comparison with data:

- Modeling variability of plasma conditions in the Io torus, Delamere, P.A. and F. Bagenal, *J. Geophys. Res.*, 108, 1276, 2003.
- Modeling temporal variability of plasma conditions in the Io torus during the Cassini era, P. A. Delamere, A. Steffl, and F. Bagenal, *J. Geophys. Res.*, 109, A10216, 2004
- Radial variations in the Io plasma torus during the Cassini era, Delamere, P. A.; Bagenal, F.; Steffl, A., *J. Geophys. Res.*, 110, A12223, 2005

Key results of these studies were:

- The main variables of the torus conditions are: (1) escape of neutral material from Io (on the order of a ton/s); (2) the oxygen/sulfur ratio of these escaping neutrals (varying from 1 to 4 – not necessarily the value of 2 from SO₂ dissociation); (3) the radial transport rate; (4) the amount of hot electrons in the plasma (<1% of the background but vital); (5) the temperature of these hot electrons (not actually so important, just needs to be >20eV);
- Small perturbations in the hot electron fraction can modulate the ion composition significantly.
- Factors of ~5 are observed in the source strength – with radial transport rate seeming to increase when the source goes up, producing smaller variations in torus plasma density (about factor of 3 at most).

An undergraduate student, Adam Shinn, worked with me at CU and then with Andrew Steffl at SWRI to develop an IDL widget that takes a wide range of variables 1-4 above to allow one to vary these and see both the resulting plasma composition as well as simulate spectra at specified wavelength range and resolution. Widget available on request.

About 4 years ago we got a NASA JDAP grant to analyze all plasma data at Jupiter from Voyager, Galileo, Ulysses and New Horizons. We are slowly working on the Galileo data (it's pretty awful) and will present at the AGU. The New Horizons data analysis is part of the thesis work of a student working with Dave McComas – who will also help with Ulysses, when we get around to it.

So – for the past couple years John Richardson and I have been slowly working away at getting the capability to access and analyze the Voyager PLS data. So far we have all the

data, we have color spectrograms and spectral plots for L, M and E modes. The goal is to have all these data available online at a LASP website (and eventually PDS) in the next month or so.

After much effort we finally have the necessary pointing information from SEDR files. We have the capability of doing this in IDL. We are not using MJSANL because it is incredibly cumbersome. And I have started looking at translating LABCUR and LDCUR from fortran to IDL. But things like aging relatives, floods and teaching have slowed me to snail's pace. But I have a new batch of keen students so I have no excuse! But even with a proper response function, fitting the spectra is non-trivial.

Seriously, the issue of how to determine plasma properties from the Voyager data is a tricky one. The problem of S^{++} and O^+ having the same mass/charge has been the bane of my professional life. You can see it as a frustration or convenience that together these ions comprise about 80% of the plasma. But the uniqueness problem of trying to fit the spectra is unavoidable. It is absolutely necessary to make some assumptions about composition and/or ion temperatures. This is where the physical chemistry model will be valuable.