Voyager UVS

50 nm<λ<170 nm   Δ = 3.0 nm

Broadfoot et al., Ultraviolet spectrometer experiment for the Voyager mission, *Space Sci. Rev., 21*, 183, 1977.

Date	Paper	Atomic Database	Results
1979	Broadfoot et al., Extreme ultraviolet observations from Voyager 1 Encounter with Jupiter, *Science, 204,* 979-982	Home (DES?)	V1 - SIII, SIV, OIII only. Ne>2100 cm^{-3}, Te=10^5 K=8.6 eV. Pcooling~2 TW S^{++}(95 cm^{-3}), S^{+++} (55 cm^{-3}), O^{++} (<850 cm^{-3})
1979	Sandel et al., Extreme ultraviolet observations from Voyager 2 Encounter with Jupiter, *Science, 206,* 962-66	Home (DES?)	V2 - SIII, SIV, OIII only. X2 brighter, 40% lower Te. Ascribed GB obs of SII and OII to cold inner torus.
1980a	Shemansky, Radiative Cooling efficiencies and predicted spectra of species of the Io plasma torus, ApJ. 236, 1043	Home	Ne>2100, Te=10^5 K=8.6 eV, Pcooling 2.5 TW. S^{++}(95 cm^{-3}), S^{+++} (80 cm^{-3}), O^{++} (290-740 cm^{-3}) Admits atomic data <911 A are not well established. OII(833) << OIII (834) because no OII(539). Net model: S^{n+} production >4 a 10^{-4} cm^{-3} s^{-1} O^{n+} production >5 a 10^{-4} cm^{-3} s^{-1} S^+(25) S^{++}(95), S^{+++}(80), S^{4+}(<12) O^+(<46) O^{++}(190-740) O^{+++}(<21)
1980	Strobel & Davis, Properties of the Io plasma torus inferred from Voyager EUV data, ApJ., 238, L49-L52, 1980	NRL & Los Alamos	Match to spectrum -> composition. Absence of OII 539 -> 834 A. Te=8 x 10^4K~7eV, Thot~100eV, Fehot<5%. S^+(<300) S^{++}(500), S^{+++}(160), O^+(300) O^{++}(110) Hints at Fehot modulating S+++ O/S>0.8 -> 2, in support of SO2 source.
1980b	Shemansky, Mass-loading and diffusion-loss rates of the Io plasma torus, ApJ., 242, 1266	Home	Source<10^{27} s^{-1} due to lack of local emission near Io. Timescale ~100 d. Power~3 TW, energy deficit from pure pick-up. Te=10^5 K=8.6 eV, Ti= 4 x 10^5K=35 eV.
1981	Shemansky, Smith, The Voyager EUV spectrum of the Io plasma torus, JGR, 86, 9179	Home	V1 – "a collisional model" Fehot=0.05%, Thot=8 x 10^4K~600eV, Ne=1850 S^+(44±20) S^{++}(160), S^{+++}(220), S^{4+}(<11) O^+(50) O^{++}(340) O^{+++}(<17) τ~months, ΣOn+/ΣSn+ = 0.9

1981	Broadfoot et al., Overview of Voyager ultraviolet spectrometer results through Jupiter encounter, JGR, 86, 8259-8284, 1981	Home (DES)	Torus analysis based on Shemansky & Smith 1981. S^+(44±20) S^{++}(160), S^{+++}(220), S^{4+}(<11) O^+(49) O^{++}(336) O^{+++}(<17)
1982a	Sandel, Broadfoot, Discovery of an Io-correlated energy source for Io's hot plasma torus, JGR, 87, 2231		All UVS data from V1+V2 (44 days). Just 685 A (SIII+OIII) Variation in brightness with phase of Io. Peak at LT=19:00, SysIII comparison with GB observations
1982b	Sandel, Broadfoot, Io's hot plasma torus: A synoptic view from Voyager, JGR 87, 212		V1 in/outbound -> dusk brighter than dawn – 25% V2 3/8 cases where no dawn/dusk effect No system III effect
1982	Shemansky, Sandel, The injection of energy into the Io plasma torus, JGR, 87, 219-229		Te ~ constant for 0.5 yr with short-term variations. System III variations in Te. Energy balance using primarily SIII 685A Te hotter LT= 22:30 dusk vs 10:30 dawn e- heating: ion collisional heating too slow (6-10d). Fehot <1% (Scudder 1981, Shamansky 1980)
1983	Brown, Pilcher, Strobel, Spectrophotometric studies of the Io torus, Physics of the Jovian Magnetosphere, Dessler (ed), CUP	various	
1987	Shemansky, Ratio of oxygen to sulfur in the Io plasma torus, JGR, 92, 6141	DES	V1/V2 comparison. Model + data – Collisional diffusive equilibrium. O:S ~ equal. OII, SII, SIII – plus GB OI, SI – Skinner & Durrance 1986 Big changes in 833/834 collision strengths. OII/OIII dependence on Te. Argues for S(O)/S(S)~4. Includes CHEX – which removes O^{++}
1988	Sandel, Dessler, Dual periodicity of the jovian magnetosphere, JGR, 93, 5487		Confined to SIII – looking for System III & IV variations. (pity in hind sight given later work showing SI and SIV more) 42 days of V2 data (235 scans). Also nKOM Lots of ideas – not any solid conclusions

1992	Dessler, Sandel, System III variations in apparent distance of the Io plasma torus from Jupiter, GRL, 19, 2099		Looking at location of peak emission – varying in distance from Jupiter (0.1-0.2 RJ) – different for dawn & dusk – driven by tail flows (IG, BK) but why modulated by System III? When modified for 0.12 RJ offset of OTD the modulation on dawn disappears – but not dusk.
1992	Bagenal, Shemansky, McNutt, et al., The abundance of O++ in the jovian magnetosphere, GRL, 19, 79-82	DES	GB – B, S, J 1983 – limits. Moos (HUT) O++ detection at 1661/6 A Used UVS data analyzed Don Shemansky at 5.75 vs. 8.25 Rj Worked on 600A OIII feature. Tries to explain lack of OIII by BSJ and Moos as due to lack of Fehot.
1993	Smith, Chutjian, Mawhorter, Williams, Shemansky, Excitation of positive ions by low-energy electrons: relevance to the torus, JGR, 98, 5499-5504		Lab experiments to determine cross sections for e- excitation. Mostly MgII with little on OII.
1995	Herbert, Sandel, Radial profiles of ion density and parallel temperature in the Io plasma torus during the Voyager 1 encounter	COREQ	Radial profiles – data = V1 O++/O+ least well-determined so given low weight. O++ profile in agreement withB92 (from Shemansky) Derives radial profiles of ne, Te and composition that are compare with B94. Infers T|| from H – very noisy.
1995	Taylor et al. Comparison of the Voyager 1 ultraviolet spectrometer and plasma science measurements of the Io plasma torus	CITEP COREQ	V1 - 48 spectra averaged to make average at 5.85 ± 0.75 RJ Factor 1. 06 to 2.3 to correct model lines to fit data. Why does using B94 composition (from Shemansky) with COREQ not fit? Used Holberg 1991 correction to UVS instrument response (~40-60%).
1997a	Volwerk, et al. Evidence for short cooling time in the Io plasma torus. GRL, 25, 1147-1150	COREQ	If there is a lack of correlation between dawn-dusk ansas in brightness then there must be a <~2 hr cooling time. This requires high density (10,000) and question about source of electron heating.
1997b	Volwerk, Systems III and IV modulation of the Io phase effect in the Io plasma torus, JGR, A11, 24, 403-24,410	COREQ	System III & IV modulation of the Io phase effect (~30%). Cleaner at dawn (where dimmer, farther) than at dusk (brighter, closer). Maybe part of problem is that SIII emissions (less variable) dominate the total brightness.

2000	Herbert, Sandel, Azimuthal variation of ion density and electron temperature in the Io plasma torus, JGR, 105, 16035-16052	COREQ	Azimuthal variations in density and Te. 47 huors of V1 data. Empirical fits to System III, IV, LT, IPE functions of brightness. Explained as Birkeland currents.

GB=ground-based, DES = Don E. Shemansky, Fehot=fraction of hot electrons, Thot=temperature of hot electrons
SI=S SII=S^+ SIII=S^{++} SIV=S^{+++} SV=S^{4+} OI=O OII=O^+ OIII=S^{++} OIV=S^{+++} OV=S^{4+}
COREQ =
CITEP=
CHIANTI =
CHEX = charge exchange
1980 – blue colored date means also included under Neutral Cloud Theory bibliography
1992 – green colored date means also included under Torus Variability bibliography

International Ultraviolet Explorer (IUE) & Hopkins Ultraviolet Telescope (HUT) on Astro-1,2

117.5 nm<λ<195 nm Δ = 1.1 nm & 41.5 nm<λ<186.4 nm Δ = 0.3 nm

Date	**Paper**	**Atomic Database**	**Results**
1983	Durrance, Feldman, Weaver, Rocket detection of UV emission from neutral oxygen & sulfur in the Io torus, Ap.J., 267, L125-L129		May 1981 sounding rocket – 115-175 nm Δ = 1.2 nm. SI (1425A) , OI (1304). OI:SI ~ 2:1 Lack of OIII at 1664A
1981	Moos, Clarke, Ultraviolet observations of the Io torus from the IUE observatory, ApJ, 247, 354-361	Strobel& Davis 1980	3 in 1979, 1 in 1980 – 8 hours each SII, SIII, weak OIII, SIV Ne~2000 Te~10eV τ~80 d S^+(140) S^{++}(320-160), S^{+++}(19, 40), O^{++}(110) OI~12-25 S(O)~2 x 10^{27} s^{-1} , SI ~23-47 S(S)~4 x 10^{27} s^{-1}
1983	Moos et al., IUE spectrum of the Io plasma torus: Identification of the 5S2->3P2,1 transition of SIII, ApJ, 275, L19-L23	Various	Neutrals from Durrance rocket. Sept 1982 13.4 hr exposure Te=8 x 10^4 K~7 eV (Brown & Shemansky 1982)
1985	Moos et al., Long-term stability of the Io high-temperature plasma torus, ApJ, 275, L19-L23	Various	13 obs. 1979-1984 – only small variations Te=5-6 x 10^4 K~4-5.5 eV ±<10% Compared 5, 6, 7 RJ. Calculated mixing ratio vs. Te ~and τ~40-120d c.f. Smyth & Shemansky 1983 S^+/Ne~0.11±28% S^{++}/Ne~0.36±4%, S^{+++}/Ne~0.023±<21%
1991	Moos et al., Determination of ionic abundances in the Io torus using the Hopkins Ultraviolet Telecope, Ap. J., 382, L105-L108		HUT ~1274s observation of east=dawn ansa 834A assumed all OII. Ne~2000. L~4 RJ S^+(356) S^{++}(436), S^{+++}(81), O^+(530)
1994	Hall, Bednar, Durrance, Feldman, McGrath, Moos, Strobel, HUT determination of the Io torus electron temperature, Ap. J., 420, L45-L48	COREQ	HUT – 1990 – Compared S2+ and S3+ line ratios to get Te. T(S2+)~2.7-4.8eV, T(S3+)~4.4-8.2 eV Dusk ~0.5 eV hotter

Extreme UltraViolet Explorer - EUVE

7.0 nm<λ<76.0 nm   Δ = 0.1-0.2 nm

Abbott et al. Astrophys. J., Suppl. Ser., 107, 451, 1996.

Date	Paper	Atomic Database	Results
1994	Hall et al., Extreme Ultraviolet Explorer satellite observation of Jupiter's Io plasma torus, Ap. J., 426, L51-L54		2 days in 1993 = 1.1 Io periods. Time-tagged O/S~2 (c.f. Shemansky 1.3) Te~3-10 eV, Fehot<1% Na+/Ne~1% SIII 680, OII 539. Modeled with Te=5eV SysIII variation <20%, Dawn-dusk~2.3-2.7 S^+/Ne~0.08-0.15 S^{++}/Ne~0.06-0.17, S^{+++}/Ne~0.016-0.036 O^+/Ne~0.4-0.66 O^{++}/Ne~0.008-0.017
1995	Hall et al., Io torus EUV emissions during the Comet Shoemaker-Levy/9 impacts, GRL, 22, 3441-3444		Emissions stable to ~20% (contrary to 2 Science papers claiming 30-50% decline - actually due to Earth atmos. Absorption)
1998	Gladstone, Hall, Recent results from EUVE observations of the Io plasma torus and Jupiter, JGR, 103, 19927-19933	COREQ	1992-1996 EUVE – 83 orbits June 19-24 1996. Dawn-dusk asymmetry ~20-30% Ne=1000, Te=4eV – model (not fit to data) S^+/Ne~0.17 S^{++}/Ne~0.18, S^{+++}/Ne~0.017 O^+/Ne~0.37 O^{++}/Ne~0.01
1998	Herbert, Hall, Disentangling electron temperature and density in the Io plasma torus, JGR, 103, 19915-19925	Osterbrock	Lack of collision strengths 350-600 A Separate Ne and Te – anticorrelated Used Bagenal 1994 -> profiles. Fit 5 species, NeNi, Te, plus collision strengths to get 78 variables, 99 equations! Gets results consistent with B94 because started with that? S^+/Ne~0.1 S^{++}/Ne~0.2, S^{+++}/Ne~0.02 O^+/Ne~0.3-0.4 O^{++}/Ne~0.03
2001	Herbert, Gladstone, Ballester, Extreme Ultraviolet Explorer of the Io torus: improved spectral resolution and new results, JGR, 106, 26293-26309	COREQ CHIANTI	EUVE summary. 165 h during I24 + 1996 during J0 of GLL Issues with EUV cross-sections. Used CHIANTI for S+ Both underestimate OII and SIII 1996 brighter than 1999. Composition with time.

Hubble Space Telescope - HST

GHRS 244.4 nm<λ<249.1 nm Δ = nm STIS 115 nm<λ<172 nm Δ =

Date	Paper	Atomic Database	Results
1993	McGrath et al., Detection of [OII] 2471 from the Io plasma torus, Ap.J., 415, L55-L58		GHRS. Detection of OII 2471 N(O+)/Ne~0.26±0.05 in agreement with Moos (IUE) but not Shemansky. Good review of O+/O++ issues. Differences with Voyager could be either Ne or Te
2003	Herbert, Schneider, Hendrix, Bagenal, HST observations of sulfur ions in the Io plasma torus: New constraints on the plasma distribution, JGR, 108, 1167	COREQ CHIANTI	STIS. Late 1999 and 2000. GLL orbits C23, I24, I27 Like Herbert 1999, used Bagenal 1994 -> profiles, then fit data with 3D model – to derive composition vs. R Te~4 eV. No significant variation with SysIII. Used both CHIANTI and COREQ – with major differences in S++/S+ but not in S+++/S++ - biggest factor ~2-2.5 S+ more variable and more confined to CentEq – equiv. to 40% colder. Peak closer to Jupiter.

Far Ultraviolet Spectroscopic Explorer - FUSE

99.5 nm<λ<118.7 nm   Δ = 0.026 nm

Moos et al., ApJ., 538, L1, 2000

Date	Paper	Atomic Database	Results
2001	Feldman, Ake, Berman, Moos, Sahnow, Strobel, Weaver, Detection of chlorine ions in the FUSE spectrum of the Io plasma torus, ApJ., 554, L123,	CHIANTI 3.0	Jan 2000 5 orbits Primary focus detection of Cl++ ions at 1% of torus.
2004	Feldman, Strobel, Moos, Weaver, The Far-ultraviolet spectrum of the Io plasma torus, Ap.J., 601, 583-591	CHIANTI 4.0	Jan 2001 5 orbits. Te~6.9 eV, S+:S++:S+++ = 0.30:1:0.23 – paper 1 = 0.41:1:0.17 – paper 2 = 0.30:1:0.15 – Steffl I – Discussion of suprathermals, Kappas, Ti=60-70 eV

Cassini UVIS

56.1 nm<λ< 118.1nm EUV   114 nm<λ< 191.3nm FUV Δ = 0.3 nm

Esposito et al., The Cassini Ultraviolet Imaging Spectrograph, *Space Sci. Rev., 115*, 299-361, 2004.

Date	**Paper**	**Atomic Databa**	**Results**
2004a	Steffl, Stewart, Bagenal, Cassini UVIS observations of the Io plasma torus. I: initial results, *Icarus, 172,* 78-90	CHIANTI	Overview. Fig 3 = Aeff from Bill McClintock. Fig 5 = Average EUV spectrum over 164 spectral images – concentrated in 6-7.2 RJ Comparison of V2 UVS, EUVE and UVIS system 3 variations. Temporal events - correlated with aurora? – mostly in SIII 680 A
2004b	Steffl, Bagenal, Stewart, Cassini UVIS observations of the Io plasma torus. II: radial variations, *Icarus, 172,* 91-103	CHIANTI 4.2	Radial variations. Jan 2000 scan Estimated 10% difference between COREQ and CHIANTI O+/O++ issues. O++ constrained by 703 (except SIII at 702) and 1666 A (first detected by Moos et al. 1991). Role of hot electrons (kappa fn).
2006	Steffl, Bagenal, Stewart, Cassini UVIS observations of the Io plasma torus. III: Observations of temporal and azimuthal variability, *Icarus, 180,* 124-140	CHIANTI 4.2	System III & IV. 4 pages of review. Weak variation in O+ and S++. Strong variations in S+ and S+++ - anticorrelated Periodogram
2006	Steffl, Bagenal, Stewart, Cassini UVIS observations of the Io plasma torus. IV: Modeling temporal and azimuthal variability, *Icarus, 180,* 124-140	CHIANTI 4.2	System III &IV. Fit functions to system III and IV variations – modulation of electrons Table of production and loss lifetimes for different species via different processes Role of hot electrons
2011	Yoshioka, Yoshikawa, Tsuchia, Kagitani, Murakami, Hot electron component in the Io plasma torus confirmed through EUV spectral analysis, JGR, 116, A09204	Chianti 6.0.1	Concentrated on 5.9 RJ. 30 images. <64.2 nm ignored because of issues with atomic data. Thot~350 eV (from Frank & Paterson). 6 parameters: Electron density, Te, Fehot, O+/S++, S+/S++, S+++/S++ O++/O+ assumed 0.1, S4+/S++ assumed 0. 5 separate days to get Dawn-dusk asymmetry.

Hisaki / EXCEED

52 nm<λ< 148nm   Δ = 0.3-0.5 nm

Yoshikawa et al., Extreme ultraviolet radiation measurement for planetary atmospheres, magnetospheres from Earth-orbiting spacecraft (EXCEED), *Space Sci. Rev., 184*, 237-258, 2010.

Date	Paper	Atomic Database	Results
2013	Yoshioka et al., The extreme ultraviolet spectroscope for planetar science, EXCEED, *Planet. Space Sci.,* 83, 250-260		Pre-launch description of instrument, including responses, resolution, etc. Prediction of Io torus emissions.
2014	Yoshioka et al., Evidence for global electron transportation in to the jovian inner magnetosphere, *Science, 345,* 1581-1584	CHIANTI 7.1	Torus spectrum (with aurora, to be analyzed separately) 5.9-7.6 RJ summed in 0.4 RJ bins (outermost 0.8 RJ). Dawn vs. Dusk. O+/S++ fixed at 1.5 Because of concern about geocoronal contamination of the OII833A line. Fit to get Ne, Te, Fehot (assuming Thot~46 eV), S+/S++, S+++/S++ Fehot of 2-10% - seems high compared with Steffl. S+/S++ profile different dawn (decreasing) & dusk (~constant -> increasing) Last statement suggests misunderstanding of cause of E-W electric field.
2015	Tsuchiya et al., Local electron heating in the Io plasma torus associated with Io from the Hisaki satellite observation, *JGR, 120,* 10,317-10,333	CHIANTI 7.1.4	Io phase effect. EXCEED data end Dec 2013 – mid Jan 2014 (~25 days) 2 lines each for SII, SIII, SIV, Dawn & Dusk. Periodogram picks up System III, IV, Io period. Longitude explained as due to Io moving up & down relative to center of torus Big difference in System III effect for dawn vs. dusk (like Dessler, Sandel) Io phase effect shows peak emission just before Io reaches elongation – suggested due to hot electrons in tail – needs about 140 GW of power into the electrons to produce a 10% modulation 12-40% effect