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Neutral Cloud Theory:
Models of Physical Chemistry of the Io Plasma Torus

Two key players in this field are Bob Smith (1946-1991) and David Barbosa (1945-2006). Re-reading these papers has made me appreciate their major contributions. We miss their brilliance.

* Key papers
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=O^{++} OIV=O^{+++} OV=O^{4+}
NL2 = NL^2 = fluxtube content
COREQ = COllisional and Radiative EQuilibrium
CITEP= Colorado Io Torus Emissions Package
CHIANTI = http://www.chiantidatabase.org
CHEX = charge exchange
1980 – purple colored date means also included under UV emissions bibliography
1992 – green colored date means also included under Torus Variability bibliography

Date	Paper	Atomic Database	Results
1982	Shemansky, Sandel, The injection of energy into the Io plasma torus, *J. Geophys. Res., 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, Shemansky 1980)
1982	Brown, Shemansky, On the nature of SII emission from Jupiter's hot plasma torus, *Ap. J., 263*, 433-442	DES	SII emission lines from EUV to visible indicate Te~6.7 eV – and SII minor ion to SIII >5.9 RJ (v. different to inner cold torus). Fluctuations in SII assumed to be due to variations in Te. Ionization theory suggests electrons not sole control of ionization state – hints at CHEX
1982	*Johnson, Strobel, Charge exchange in the Io torus and exosphere, *J. Geophys. Res., 87,* 10,385-10,393		CHEX – 25 reactions calculated. For simple model of neutrals (Smyth), ne, Te -> composition & rates. No radial transport.

1983	Brown, Shemansky, Johnson, A deficiency of OIII in the Io plasma torus, *Ap. J., 264*, 309-323	DES & Johnson	Lack of detection of OIII 5007A – previous data/models show O+/O++ varies from 100 to 2.4 Johnson proposes CHEX - will remove O++ ions Shemansky presents model of chemistry w/diffusion but no CHEX, which is discussed more as a source of neutrals
1983	Smyth, Shemansky, Escape and ionization of atomic oxygen from Io, *Ap. J., 271*, 865-875		Uses OI detection by Brown 1981 (6300) plus torus model to produce a model of the neutral cloud of O around Io's orbit. Adds assumed similar S cloud. Mass and power source too low for torus, even with long diffusion time scales. No ion chemistry – just electron temperature and density. No CHEX in model but recognizes potential importance.
1983	Brown, Pilcher, Strobel, Spectrophotometric studies of the Io torus, *Physics of the Jovian Magnetosphere*, Dessler (ed), CUP	various	Summary of observations and models to date. Useful reference for spectral lines and emission processes.
1985	Linker, Kivelson, Moreno, Walker, Explanation of the inward displacement of Io's hot plasma torus and consequences for sputtering sources, *Nature, 315*, 375-378		Aim to explain peak of NL2 profile inward of Io's orbit. Neutral cloud generated by ejection of neutrals from Io's equator at speeds>escape. Assumes electron-impact ionization with life times of ~40 hours. Prefers S_2^+ production because easily lost via dissociative recombination. Assumes uniform Ne and Te – probably major issue. Needs spike in f(v) of escaping neutrals to confine peak to 5.7 RJ.
1985	*Smith, Strobel, Energy partitioning in the Io plasma torus, *J. Geophys. Res., 90*, 9469-9493	Strobel NRL Johnson	Model with everything! Starts from f(v) for pick-up ions and evolves velocity distribution. Assumes ne=2000 Includes ionization, CHEX, radiation, radial transport. Variables: tau, Q, Te neutral density: no~22 cm-3 only, ns~0.1 no, ns~2no Driven by O+~660 cm-3 and O++<5 cm-3
1985	Moreno, Newman, Kivelson, Ion partitioning in the hot Io torus: Influence of S2 outgassing, *J. Geophys. Res., 90*, 12065-16072	Johnson & Strobel, Brown 83, DES	Aim to address low O++ density with S2 rather than SO2 source. Model not well explained but seems a 0-D (cubic-cm) model Ionization, CHEX, radiation Variables: Fehot (1keV), Q, tau, Ti -> steady state Derives S2~60% SO2, Fehot~0.05%, tau~35days
1986	Moreno, Barbosa, Mass and energy balance in the cold Io torus, *J. Geophys. Res., 91*, 8993-8997		Cold torus. Model not well explained but seems a 0-D (cubic-cm) model Ionization, CHEX, radiation, tau~140-710 days Includes 2-step recombination that removes oxygen: O+ + SO2 ->O(fast) + SO2+ then SO2+ + e- -> O(fast) + SO(fast)

1987	Shemansky, Ratio of oxygen to sulfur in the Io plasma torus, *J. Geophys. Res., 92*, 6141-6146	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^{++}
1987	Strobel, Energetics, luminosity, and spectroscopy of Io's torus, in Time-Variable Phenomena in the Jovian System, Belton, West, Rahe (eds) NASA SP-494		Summary of studies to date – emphasizing the energetics. Table of composition showing variations as interpretation of emissions changed from Voyager UVS onwards to Shemansky 1987.
1988	*Barbosa, Moreno, A comprehensive model of ion diffusion and charge exchange in the cold Io torus, *J. Geophys. Res., 93,* 823-836		Inner cold torus. Comprehensive model is right phrase – includes electron collisions, radiative losses, CHEX, radial transport and diffusive equilibrium for latitudinal structure. Concludes SO2 can provide all neutrals, when molecular reactions included S^+(220) S^{++}(340), S^{+++}(40), O^+(800) O^{++}(90) for hot torus. *(would be great to re-do with proper neutral kinetics & chemistry and modern atomic data)*
1988	*Shemansky, Energy branching in the Io plasma torus: The failure of neutral cloud theory, *J. Geophys. Res., 93,* 1773-1784	DES	To match ionic states with realistic (longer) timescales additional energy is needed over ion pick-up Smith & Strobel 1985 pointed out hot electrons – but DES argues they underestimated radiative losses Assumes maxwellians (argues that macroscopic OK) Notes that CHEX rates have energy dependence Notes that SII radiative coefficient has increased significantly Key parameter SII/SIII – states observations <1, NCT gives 10-20 depending on tau Also addresses "Pilcher & Morgan case" of Ne ~10^4 v. hard to do. Concludes that additional energy either has to come from CHEX and PU near Io – OR – hot e- (except Sittler & Stobel put limits) Notes CHEX can remove O, compo similar to Smith & Stobel except for amount of OIII Fig 1 – Radiative cooling coefficients "Details of these calculations will be published at a later date" "These results are based on the latest available collision strength and electronic structure data. Details will be given in a later publications" – no ref.

1988	Smith, Bagenal, Cheng, Strobel, On the energy crisis in the Io plasma torus, *Geophys. Res. Lett., 15,* 546-	Strobel	Proposed inwardly-diffusing energetic ions supplied the additional energy to the torus. N(S)~6, N(O)~ 30, Ne~2000 cm^{-3}
1989	*McGrath, Johnson, Charge Exchange cross sections for the Io plasma torus, *J. Geophys. Res., 94,*		30 CHEX reaction cross-sections calculated vs. ion energy.
1990	Shemansky, Critical quantities for solar system science in atomic and molecular reactions, *AIP conference proceedings, 206,* 163		For torus quotes ionization Brown, Shemansky, CHEX Johnson 1990, McGrath & Johnson 1989. Argues that enhanced recombination rates may be needed to explain low abundance of SII
1994	*Barbosa, Neutral cloud theory of the jovian nebula: anomalous ionization effect of suprathermal electrons, *Ap. J., 430,* 376-376		Good review of work to date. NCT model from 4 to 7 RJ. CHEX from Johnson, quotes emission rates. Assumes t~68 days, 5/cc hot electrons >5.7 RJ. Argues hot electrons only contribute 10-20 of energy budget and can be fully explained with pick-up-generated ion cyclotron waves (as per Barbosa et al. 1985).
1995	Matheson, Shemansky, Chemistry and transport in the Io torus ramp, *Icarus*, submitted	COREQ	Radial model of torus chemistry Te fixed to Sittler profile. Explored effects of rate of radial transport. Slow (60d) close to 6 RJ, moderate (20d) moderate better at 7.2 RJ. Composition – ni/Ne 6 RJ - S^+(0.13) S^{++}(0.18), S^{+++}(0.02), O^+(0.42) O^{++}(0.015) 7.75 RJ - S^+(0.13) S^{++}(0.09), S^{+++}(0.02), O^+(0.26) O^{++}(0.22)
1996	Herbert, A simple transport model for the Io plasma torus “ribbon”, *Geophys. Res. Lett., 23*, 2875-2878		Location of Ribbon modeled with radial transport and pressure gradients. Uses NL^2 profile to derive DLL. Seems to completely ignore role of neutral cloud.
1998	Smyth, Marconi, An explanation for the east-west asymmetry of the Io plasma torus, *J. Geophys. Res., 103,* 9091-9100		Models S+, S++ emissions – Dawn-dusk asymmetry Uses transport+Edawn-dusk+SIII+OTD+Io’s orbit. Tau~25 d at 7RJ
1998	*Schreier, Eviatar, Vasyliunas, A two-dimensional model of plasma transport and chemistry in the jovian magnetosphere, *J. Geophys. Res., 103,* 19,901-19,913	CITEP	Physical chemistry model (2D) based on Richardson model. Input neutral profiles, O/S~5 Calculated electron properties, ion composition, temperature. Matched to Bagenal (1994) empirical model. Required additional heating of outer torus. Preferred inward moving ring current ions as source of heating.

2001	*Lichtenberg, Thomas, Fouchet, Detection of S (IV) 10.51 micron emission from the Io plasma torus, *J. Geophys. Res., 106,* 29,899-29,910		IR observations of S3+ combined with Voyager UVS to constrain a geometrical model (using CITEP) and a neutral cloud model (based on Shemansky 1988) Derives short (8 day) timescale and low production rates V1 and V2 conditions with change in ionization rates since Shem88.
2003	*Delamere, Bagenal, Modeling variability of plasma conditions in the Io torus, *J. Geophys. Res., 108,* 1276	CHIANTI	0-D cm^3 model. Solve for steady-state flow of mass and energy. Emission rates vs. Te from CHIANTI Ionization – factor x2 in S->S+ in the literature Recombination from Lichtenberg & Thomas 2001 Sensitivity to Fehot, Tehot, O/S, S_N, tau V1, V2, Cassini
2003	Smyth, Marconi, Nature of the iogenic plasma source in Jupiter's magnetosphere. I. Circumplanetary distribution, *Icarus, 166,* 85-106		Io neutral source – S, O ~0.5 km/s 3-D neutral cloud model shaped by ionization and CHEX
2004	Hill, Dessler, Longitudinal variation of ion temperature in the Io plasma torus, *J. Geophys. Res., 109*, A04206		SystemIII longitude variations in Ti (perp 20-45 eV, par 10-30eV) from Brown 1995, Thomas 2001, Schneider 1997 Uses VIT4 to derive Pederson conductance for N, S and argues pick-up energy controlled by ionospheric conductance $(SigN+SigS)^2$
2004	Thomas, Bagenal, Hill, Wilson, The Io neutral clouds and plasma torus, in Jupiter, Bagenal, Dowling, McKinnon (eds), CUP		Review of observations and models of both neutral clouds and torus. Extensive discussion on radial transport.
2004	Delamere, Steffl, Bagenal, Modeling temporal variability of plasma conditions in the Io torus during the Cassini era, *J. Geophys. Res.,*	CHIANTI	Dust measurements show x1000 increase in flux from Io in Sept 2000 Cassini UVIS sees decrease from Oct 2000 through Mar 2001. Modeled with 2003 model with factor of 3.5 increase in neutral production rate with time-scale of 22.5 days
2005	*Delamere, Bagenal, Steffl, Radial variations in the Io plasma torus during the Cassini era, *J. Geophys. Res., 110,* A12223	CHIANTI 4.2	Modeled UVIS composition vs. radial distance with 1-D model (latitudinally averaged) with proscribed neutral cloud profile. Solves for conservation of mass & energy Parameters: S_N, O/S, tau, Fehot, Tehot, Explores sensitivity to transport, neutral source, Fehot.

2005	Smyth, Marconi, Nature of the iogenic plasma source in Jupiter's magnetosphere. II. Near-Io distribution, *Icarus, 176,* 138-154		Near Io – neutral clouds of O, S – from exobase to ~20 RIo. Limited electrodynamics. Ionization & CHEX. Inner vs. outer region – see Fig 10. Net mass-loading 111 kg/s
2007	Wu, Hill, Wolf, Spiro, Numerical simulation of fine structure in the Io plasma torus produced by the centrifugal interchange instability, *J. Geophys. Res., 112,*		Rice Convection Model for IPT - models radial transport with flux-tube interchange. No chemistry. Found ~1° longitude "fingers". Outward transport faster than inward.
2008 2008	Steffl, Bagenal, Stewart, Cassini UVIS observations of the Io plasma torus. IV: Modeling temporal and azimuthal variability, *Icarus, 194,* 153-165	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
2008	Herbert, F., N. M. Schneider, and A. J. Dessler, "New description of Io's cold plasma torus", J. Geophys. Res., 113		
2011	Smyth, Peterson, Marconi, A consistent understanding of the ribbon structure for the Io plasma torus at the Voyager 1, 1991 GB, and Galileo J0 epochs, *J. Geophys. Res., 116,* A07205	CHIANTI 5.2.1	Attempts to match all Voyager and Galileo data with a 4-D model that includes Io phase, SIII longitude, R, Latitude Emphasis on S+ emissions Argues for big changes in Inner/Outer torus ratios between epochs: 1991 (GB epoch) outer/inner densities ~1.3 x Voyager 1995 (GLL) outer/inner densities ~3.9 x Voyager
2011	Hess, Delamere, Bagenal, Schneider, Steffl, Longitudinal modulation of hot electrons in the Io plasma torus, *J. Geophys. Res., 116,* A11215		Longitude modulation of emissions. Argues for magnetic field control. Says hot electrons come from Alfvenic currents. Power from inward-moving fluxtubes is not modulated by longitude. To account for the beating between SystemIII, SystemIV : - SystemIV controls the inward motion of empty fluxtubes, - System III controls efficiency of power transfer to the electrons (via magnetic field variations at the foot of the fluxtube in the ionosphere).
2014	Grieve et al., Electron-impact excitation collision strengths and theoretical line intensities for transitions in SIII, *Ap. J., 780,* 110	CHIANTI 7.1	Calculations of collision strengths and excitation of lines of SIII at various regions in the EUV Incorporated into CHIANTI database Comparison with line-ratios from Feldman in FUSE & EUVE observations. Also discusses kappa functions.

2016	Copper, Delamere, Overcast-Howe, Modeling physical chemistry of the Io plasma torus in two dimensions, *J. Geophys. Res., 121*		Combines Steffl 2008 (azimuthal) with Delamere 2005 (radial) variations Uses Bagenal 1994 for outer boundary conditions. Needs hot (270 eV) electrons (fehot~0.2%) modulated with System III&IV Transport 6-10 RJ ~43Days. Needs lower Pederson conductance to produce subcorotation of ~1 km/s
2017	Yoshioka, K., et al., Radial variation of sulfur and oxygen ions in the Io plasma torus as deduced from remote observations by Hisaki, *J. Geophys. Res.*, 122, 2999-3012,	CHIANTI 8.0	Hisaki data 219 min in Nov 2013 – radial profiles of emissions Radial variations in ion species and electron properties modeled with line-of-sight integration Composition similar to Voyager (Nerney) and Cassini (Steffl) Radial transport ~30 days

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NL2 = NL^2 = fluxtube content
COREQ = COllisional and Radiative EQuilibrium
CITEP= Colorado Io Torus Emissions Package
CHIANTI = http://www.chiantidatabase.org
CHEX = charge exchange
1980 – purple colored date means also included under UV emissions bibliography
1992 – green colored date means also included under Torus Variability bibliography