Chapter 8

Conclusions

There is something fascinating about science. One gets such wholesome returns of conjecture out of such a trifling investment of fact.
Mark Twain

8.1 Summary of the Thesis

For thirty years observers and modelers have studied the gaseous clouds escaping from Io. The most heavily observed constituent of the clouds, sodium, has continued to demand attention due to the many ways its escape from Io manifests itself, including jets of fast sodium seen escaping from Io's atmosphere and a banana shaped cloud extending close to one million kilometers ahead of Io in its orbit.

The escape of oxygen from Io also exhibits itself in exciting and complex ways. The excitation of its emission by the plasma which acts to ionize it makes the analysis of its brightness morphology both difficult and tantalizing: understanding the distribution of neutral oxygen is intimately coupled with an understanding of the plasma torus. The fact that oxygen is the most abundant species in the neutral clouds and the plasma torus makes the study of oxygen all the more important.

In this thesis I used models and observations of Io's neutral features to study the escape of Io's atmosphere and the source regions of the plasma torus. These studies were complicated by the inherent difficulties involved in studying extremely time-variable phenomena. In spite of these difficulties, I have discovered a new feature of

Io's corona, advanced the understanding of previously observed phenomena with unique observations, helped compile an extensive and unique data set, developed a framework for analyzing future observations, and made predictions of the shape and interactions of the neutral clouds with the plasma torus. Below I summarize the main goals of each chapter. In the following section I describe my success in obtaining these goals and list the major accomplishments of this thesis.

The physical processes which are important for understanding the neutral clouds were reviewed in Chapter 2. The sodium neutral cloud is observed both in emission and absorption through the process of resonant scattering; oxygen line emission is excited by electron impacts which is strongly dependent on the state of the plasma torus. The dominant loss mechanism that forms the corona and neutral clouds is sputtering off the atmosphere and surface by plasma torus electrons. Neutral atoms are lost from the system by ionization. Ionization of sodium atoms occurs primarily through electron impacts. Oxygen is lost mainly by charge exchange with plasma torus ions. Sulfur exhibits a mix of the two mechanisms. Between their ejection from the atmosphere and their loss into the plasma torus, the paths of the atoms are determined by the force of gravity. Sodium atoms also experience a slight perturbation from radiation pressure.

Chapter 3 presented a new series of mutual event observations of Io's sodium corona. Mutual events have been the only method for determining the shape of the sodium corona. Data from three telescopes were analyzed to search for time variability and spatial asymmetries in the sodium corona.

A jet of fast sodium has been observed to extend many Jovian radii from Io (Goldberg et al. 1984; Pilcher et al. 1984). This feature, however, had never been observed close to its source in Io's ionosphere. Galileo observations of this fast sodium jet were presented in Chapter 4. Implications of the observation for Io's ionosphere were discussed.

Chapter 5 contained a description of the neutral cloud model that is used in

Chapters 6 and 7 to study Io's corona and neutral clouds. In addition to describing the model itself, I developed a new method for parameterizing the plasma torus such that the state of the plasma can be described as a function of the position relative to Jupiter and the magnetic longitude. The description relies heavily on observations of the torus (Bagenal 1994; Schneider and Trauger 1995; Brown 1994) and includes the effects of Jupiter's offset tilted dipole field, the dawn-dusk electric field, and observed variability of the torus with magnetic longitude. I also discuss several tests of the model including the first modeling analysis of the observed dependence of the north/south brightness ratio in the sodium cloud with magnetic longitude.

A detailed study of Io's neutral corona is presented in Chapter 6. After first determining the velocity distribution of neutral atoms from the exobase which best models the sodium corona observed in Chapter 3, I describe the effects of variations in the source distribution and in the loss by the plasma torus. I also present a model analysis of the sodium corona asymmetry which I discovered. The chapter ends with a comparison of the oxygen and sodium coronae based on HST/STIS observations of oxygen (Wolven et al. 2001).

Chapter 7 focused on the similarities and differences in the extended neutral clouds of sodium and oxygen. A model analysis was presented to explain morphological features in both the column densities and emission intensities of modeled images. In particular, I discuss the strong dependence on the observing geometry of the clouds, the variations in sodium brightness with orbital phase, and the effects of the plasma torus on oxygen observations. I also present an archive of sodium images which will be used in conjunction with the neutral cloud model to study variability in Io's neutrals.

8.2 Major Results

The modeling and observational studies presented here have yielded answers to several outstanding questions regarding Io's neutral clouds. These results are summarized here for the different regions which I studied:

(1) Io's Corona:

- Comparison of mutual events from 1985, 1991, and 1997 have demonstrated remarkable stability in the sodium corona despite large short term event-to-event variations. This implies that although Io's atmosphere and the plasma torus are both highly variable, on average each remain roughly constant.
- I discovered a previously undetected asymmetry in Io's corona between the sub-Jupiter and anti-Jupiter hemispheres: the corona above the inner hemisphere is denser than above the outer hemisphere. This asymmetry implies asymmetric loss from Io's exobase. Approximately 70% of the source sodium in the corona was ejected from the sub-Jupiter hemisphere.
- The oxygen corona has been observed to be more extended than the sodium corona. If this difference is due to column density differences between oxygen and sodium it implies that oxygen is ejected from Io at a faster average velocity. The longer oxygen lifetime cannot explain the magnitude of the observed difference. The increased velocity may be due to differences in the sputtering of the two species or may indicate that oxygen escapes from Io due to a second mechanism in addition to any loss by sputtering. The difference may also result from the fact that the electron temperature in the plasma torus decreases close to Io as observed by Voyager.
- The mechanism for creating the inner/outer asymmetry in the sodium corona is not responsible for creating an asymmetry in the oxygen column density. It is not possible to distinguish whether the upstream/downstream oxygen asymmetry is a result of differences in the emission rates of oxygen between the two regions or indicative of column density differences without

detailed modeling of the effects of Io's interaction with the torus on the plasma parameters.

- The variable and complex apparent motions and brightness variations of the plasma torus relative to Io cause large variations in the neutral lifetime at Io. These variations affect both the brightness in the the corona and the rate at which the density decreases as a function of distance from Io. The different ways in which the torus changes introduce local time, magnetic longitude, and non-periodic variability in the corona.
- A confirmation of the source mechanism described by Smyth and Combi (1988b) for the east/west brightness ratio in the corona was presented. The explanation for this asymmetry was expanded by showing that the column density at Io's surface does not change as a function of Io's orbital phase and that the asymmetry results from a change in the spatial extent of the corona.

(2) Io's fast sodium jet:

- I presented the first image of Io's fast sodium jet within several Io radii of Io providing support for the resonant charge exchange model of the jet formation described by Wilson and Schneider (1999).
- The jet originates from a region smaller than Io's diameter implying that Io's ionosphere is concentrated near the equator, consistent with observations that the atmosphere is also denser near the equator (Feldman et al. 2000)

(3) Io's extended neutral clouds:

- The plasma torus introduces a magnetic longitude variation in the north/south brightness ratio of sodium in the neutral cloud as predicted by Trafton

(1980).

- The oxygen neutral cloud is significantly larger in extent than the sodium cloud. Observations of oxygen are difficult to make due to the fact that the oxygen emissions are faint compared to scattered light from Jupiter and telluric air glow emissions. In addition, the nature of the emission mechanism makes it difficult to extract column densities from the oxygen intensities without knowledge of the state of the local plasma.
- The large available data set of neutral sodium images combined with the neutral cloud model and near-simultaneous images of the plasma torus will help determine the large term variability in both Iogenic neutrals and plasma.

It is also important to note that although there has been a long history of observing the minor species sodium, new discoveries are still being made. I have presented in this thesis two new observational results based solely on the observations of sodium: the inner/outer asymmetry in the corona and the size of the source region of the sodium jet. Therefore it is essential to study the sodium data set, and other data sets which have not been adequately mined, for the wealth of new results which they should be expected to contain.

Bibliography

Arlot, J.-E., New constants for Sampson-Lieske theory of the Galilean Satellites of Jupiter, *Astronomy and Astrophysics*, **107**, 305–310, 1982.

Arlot, J.-E., Predictions of the mutual events of the Galilean satellites of Jupiter occurring in 1997., *Astronomy and Astrophysics*, **314**, 312–314, 1996.

Arnaud, M., and R. Rothenflug, An updated evaluation of recombination and ionization rates, *Astrophysics and Space Science, Supplement Series*, **60**, 425–457, 1985.

Bagenal, F., Empirical model of the Io plasma torus: Voyager measurements, *Journal of Geophysics Research*, **99**, 11,043–11,062, 1994.

Ballester, G. E., H. W. Moos, P. D. Feldman, D. F. Strobel, M. E. Summers, J.-L. Bertaux, T. E. Skinner, M. C. Festou, and J. H. Lieske, Detection of neutral oxygen and sulfur emissions near Io using IUE, *Astrophysical Journal, Letters to the Editor*, **319**, L33–L38, 1987.

Ballester, G. E., M. A. McGrath, D. F. Stobel, X. Zhu, P. D. Feldman, and H. W. Moos, Detection of the SO2 atmosphere on Io with the Hubble Space Telescope, *Icarus*, **111**, 2–17, 1994.

Barbosa, D. D., and M. G. Kivelson, Dawn-dusk electric field asymmetry of the Io plasma torus, *Geophysics Research Letters*, **10**, 210–213, 1983.

Belton, M. J. S., et al., The Galileo Solid-State Imaging experiment, *Space Science Reviews*, **60**, 413–455, 1992.

Bergstralh, J. T., D. L. Matson, and T. V. Johnson, Sodium D-line emission from Io - Synoptic observations from Table Mountain Observatory, *Astrophysical Journal, Letters to the Editor*, **195**, L131–L135, 1975.

Bergstralh, J. T., J. W. Young, D. L. Matson, and T. V. Johnson, Sodium D-line emission from Io - A second year of synoptic observation from Table Mountain Observatory, *Astrophysical Journal, Letters to the Editor*, **211**, L51–L55, 1977.

Binder, A. B., and D. P. Cruikshank, Evidence for an Atmosphere on Io, *Icarus*, **3**, 299, 1964.

Bouchez, A. H., M. E. Brown, and N. M. Schneider, Eclipse Spectroscopy of Io's Atmosphere, *Icarus*, **148**, 316–319, 2000.

Brown, M. E., The Structure and Variability of the io Plasma Torus, *Ph.D. Thesis*, 1994.

Brown, M. E., Periodicities in the Io plasma torus, *Journal of Geophysics Research*, **100**, 21,683–21,696, 1995.

Brown, R. A., Optical line emission from Io, in *IAU Symp. 65: Exploration of the Planetary System*, vol. 65, pp. 527–531, 1974.

Brown, R. A., The Jupiter hot plasma torus - Observed electron temperature and energy flows, *Astrophysical Journal*, **244**, 1072–1080, 1981a.

Brown, R. A., The Jupiter hot plasma torus - Observed electron temperature and energy flows, *Astrophysical Journal*, **244**, 1072–1080, 1981b.

Brown, R. A., and F. H. Chaffee, High-Resolution Spectra of Sodium Emission from Io, *Astrophysical Journal, Letters to the Editor*, **187**, L125, 1974.

Brown, R. A., and Y. L. Yung, Io, its atmosphere and optical emissions, in *IAU Colloq. 30: Jupiter: Studies of the Interior, Atmosp here, Magnetosphere and Satellites*, pp. 1102–1145, 1976.

Brown, R. A., R. M. Goody, F. J. Murcray, and F. H. Chaffee, Further studies of line emission from Io, *Astrophysical Journal, Letters to the Editor*, **200**, L49–L53, 1975.

Burger, M. H., N. M. Schneider, and J. K. Wilson, Galileo's close-up view of the Io sodium jet, *Geophysics Research Letters*, **26**, 3333, 1999.

Burger, M. H., N. M. Schneider, I. de Pater, M. E. Brown, A. H. Bouchez, L. M. Trafton, Y. Sheffer, E. S. Barker, and A. Mallama, Mutual Event Observations of Io's Sodium Corona, *Astrophysical Journal*, **563**, 1063–1074, 2001.

Chamberlain, J. W., *Physics of the aurora and airglow*, International Geophysics Series, New York: Academic Press, 1961, 1961.

Cremonese, G., F. Marzari, N. Eccli, and G. Corrain, The Io Sodium Cloud: Comparison between Observations and Numerical Models, *Icarus*, **131**, 138–151, 1998.

Dere, K. P., E. Landi, H. E. Mason, B. C. Monsignori Fossi, and P. R. Young, CHIANTI - an atomic database for emission lines, *Astrophysics and Space Science, Supplement Series*, **125**, 149–173, 1997.

Dessler, A. J. (Ed.), *Physics of the Jovian magnetosphere*, 1983.

Durrance, S. T., P. D. Feldman, and H. A. Weaver, Rocket detection of ultraviolet emission from neutral oxygen and sulfur in the Io Torus, *Astrophysical Journal, Letters to the Editor*, **267**, L125–L129, 1983.

Fang, T.-M., W. H. Smyth, and M. B. McElroy, The spatial distribution of long lived gas clouds emitted by satellites in the outer solar system, *Planetary Space Science*, **24**, 577–588, 1976.

Feldman, P. D., et al., Lyman- Alpha Imaging of the SO_2 Distribution on Io, *Geophysics Research Letters*, **27**, 1787+, 2000.

Geissler, e., P. E., Galileo imaging of atmospheric emissions from Io, *Icarus*, **285**, 870–874, 1999.

Goldberg, B. A., Y. Mekler, R. W. Carlson, T. V. Johnson, and D. L. Matson, Io's sodium emission cloud and the Voyager 1 encounter, *Icarus*, **44**, 305–317, 1980.

Goldberg, B. A., G. W. Garneau, and S. K. Lavoie, Io's sodium cloud, *Science*, **226**, 512–516, 1984.

Goldreich, P., and D. Lynden-Bell, Io, a jovian unipolar inductor, *Astrophysical Journal*, **156**, 59–78, 1969.

Hansell, S. A., W. K. Wells, and D. M. Hunten, Optical detection of lightning on Venus., *Icarus*, **117**, 345–351, 1995.

Hill, T. W., and F. C. Michel, Heavy ions from the Galilean satellites and the centrifugal distortion of the Jovian magnetosphere, *Journal of Geophysics Research*, **81**, 4561–4565, 1976.

Hinson, D. P., A. J. Kliore, F. M. Flasar, J. D. Twicken, P. J. Schinder, and R. G. Herrera, Galileo radio occultation measurements of Io's ionosphere and plasma wake, *Journal of Geophysics Research*, **103**, 29,343–29,357, 1998.

Ingersoll, A. P., Io meteorology - How atmospheric pressure is controlled locally by volcanos and surface frosts, *Icarus*, **81**, 298–313, 1989.

Ip, W.-H., and C. K. Goertz, An interpretation of the dawn-dusk asymmetry of UV emission from the Io plasma torus, *Nature*, **302**, 232, 1983.

Johnson, R. E., *Energetic Charged-Particle Interactions with Atmospheres and Surfaces*, Energetic Charged-Particle Interactions with Atmospheres and Surfaces, X, 232 pp. 84 figs., 28 tabs.. Springer-Verlag Berlin Heidelberg New York. Also Physics and Chemistry in Space, volume 19, 1990.

Johnston, A. R., and P. D. Burrow, Electron-impact ionization of Na, *Physical Review A*, **51**, 1735, 1995.

Kliore, A., D. L. Cain, G. Fjeldbo, B. L. Seidel, and S. I. Rasool, Preliminary Results on the Atmospheres of Io and Jupiter from the Pioneer 10 S-Band Occultation Experiment, *Science*, **183**, 323–324, 1974.

Kliore, A. J., G. Fjeldbo, B. L. Seidel, D. N. Sweetnam, T. T. Sesplaukis, P. M. Woiceshyn, and S. I. Rasool, The atmosphere of Io from Pioneer 10 radio occultation measurements, *Icarus*, **24**, 407–410, 1975.

Kumar, S., Photochemistry of SO2 in the atmosphere of Io and implications on atmospheric escape, *Journal of Geophysics Research*, **87**, 1677–1684, 1982.

Lellouch, E., Urey Prize Lecture. Io's Atmosphere: Not Yet Understood, *Icarus*, **124**, 1–21, 1996.

Lellouch, E., T. Encrenaz, M. Belton, I. de Pater, and S. Gulkis, Io's atmosphere from microwave detection SO2, *Nature*, **346**, 639–641, 1990.

Lyot, B., The study of the solar corona and prominences without eclipses (George Darwin Lecture, 1939), *Monthly Notices of the RAS*, **99**, 580, 1939.

Macy, W., and L. Trafton, A model for Io's atmosphere and sodium cloud, *Astrophysical Journal*, **200**, 510–519, 1975a.

Macy, W. W., and L. M. Trafton, Io's sodium emission cloud, *Icarus*, **25**, 432–438, 1975b.

Mallama, A., Light curve model for the Galilean satellites during Jovian eclipse, *Icarus*, **92**, 324–331, 1991.

Matson, D. L., T. V. Johnson, and F. P. Fanale, Sodium D-Line Emission from Io: Sputtering and Resonant Scattering Hypothesis, *Astrophysical Journal, Letters to the Editor*, **192**, L43, 1974.

Matson, D. L., B. A. Goldberg, T. V. Johnson, and R. W. Carlson, Images of Io's sodium cloud, *Science*, **199**, 531–533, 1978.

McElroy, M. B., Y. L. Yung, and R. A. Brown, Sodium Emission from Io: Implications, *Astrophysical Journal, Letters to the Editor*, **187**, L127, 1974.

McGrath, M. A., and R. E. Johnson, Charge exchange cross sections for the Io plasma torus, *Journal of Geophysics Research*, **94**, 2677–2683, 1989.

McGrath, M. A., M. J. S. Belton, J. R. Spencer, and P. Sartoretti, Spatially Resolved Spectroscopy of Io's Pele Plume and SO_2 Atmosphere, *Icarus*, **146**, 476–493, 2000.

Mendillo, M., J. Baumgardner, B. Flynn, and W. J. Hughes, The extended sodium nebula of Jupiter, *Nature*, **348**, 312–314, 1990.

Moore, C. E., M. G. J. Minnaert, and J. Houtgast, *The solar spectrum 2935 Å to 8770 Å*, National Bureau of Standards Monograph, Washington: US Government Printing Office (USGPO), 1966.

Moreno, M. A., G. Schubert, M. G. Kivelson, D. A. Paige, and J. Baumgardner, Io's volcanic and sublimation atmospheres, *Icarus*, **93**, 63–81, 1991.

Muench, G., and J. T. Bergstralh, Io - Morphology of its sodium emission region, *Publications of the ASP*, **89**, 232–237, 1977.

Murcray, F. J., and F. Goody, Pictures of the Io sodium cloud, *Astrophysical Journal*, **226**, 327–335, 1978.

Oliversen, R. J., F. Scherb, W. H. Smyth, M. E. Freed, R. Carey Woodward, M. L. Marconi, K. D. Retherford, O. L. Lupie, and J. P. Morgenthaler, Sunlit Io atmospheric [O I] 6300 Å emission and the plasma torus, *Journal of Geophysics Research*, **106**, 26,183–26,194, 2001.

Parkinson, T. D., Excitation of the sodium D line emission observed in the vicinity of Io, *Journal of Atmospheric Sciences*, **32**, 630–633, 1975.

Pearl, J., R. Hanel, V. Kunde, W. Maguire, K. Fox, S. Gupta, C. Ponnamperuma, and F. Raulin, Identification of gaseous SO2 and new upper limits for other gases on Io, *Nature*, **280**, 755–758, 1979.

Pilcher, C. B., J. H. Fertel, W. H. Smyth, and M. R. Combi, Io's sodium directional features - Evidence for a magnetospheric-wind-driven gas escape mechanism, *Astrophysical Journal*, **287**, 427–444, 1984.

Retherford, K. D., H. W. Moos, D. F. Strobel, B. C. Wolven, and F. L. Roesler, Io's equatorial spots: Morphology of neutral UV emissions, *Journal of Geophysics Research*, **105**, 27,157–27,166, 2000.

Roesler, F. L., et al., Far-Ultraviolet Imaging Spectroscopy of Io's Atmosphere with HST/STIS, *Science*, **283**, 353+, 1999.

Saur, J., F. M. Neubauer, D. F. Strobel, and M. E. Summers, Io's ultraviolet aurora: Remote sensing of Io's interaction, *Geophysics Research Letters*, **27**, 2893+, 2000.

Scherb, F., and W. H. Smyth, Variability of (O I) 6300-A emission near Io, *Journal of Geophysics Research*, **98**, 18,729+, 1993.

Schneider, N. M., and J. T. Trauger, The Structure of the Io Torus, *Astrophysical Journal*, **450**, 450+, 1995.

Schneider, N. M., D. M. Hunten, W. K. Wells, and L. M. Trafton, Eclipse measurements of Io's sodium atmosphere, *Science*, **238**, 55–58, 1987.

Schneider, N. M., D. M. Hunten, W. K. Wells, A. B. Schultz, and U. Fink, The structure of Io's corona, *Astrophysical Journal*, **368**, 298–315, 1991a.

Schneider, N. M., J. K. Wilson, J. T. Trauger, D. I. Brown, R. W. Evans, and D. E. Shemansky, Molecular origin of Io's fast sodium, *Science*, **253**, 1394–1397, 1991b.

Schneider, N. M., M. H. Taylor, F. J. Crary, and J. T. Trauger, On the nature of the λ¡SUB¿III¡/SUB¿ brightness asymmetry in the Io torus, *Journal of Geophysics Research*, **102**, 19,823–19,834, 1997.

Sieveka, E. M., and R. E. Johnson, Ejection of atoms and molecules from Io by plasma-ion impact, *Astrophysical Journal*, **287**, 418–426, 1984.

Sittler, E. C., and D. F. Strobel, Io plasma torus electrons - Voyager 1, *Journal of Geophysics Research*, **92**, 5741–5762, 1987.

Smyth, W. H., Io's sodium cloud - Explanation of the east-west asymmetries, *Astrophysical Journal*, **234**, 1148–1153, 1979.

Smyth, W. H., Io's sodium cloud - Explanation of the east-west asymmetries. II, *Astrophysical Journal*, **264**, 708–725, 1983.

Smyth, W. H., Neutral cloud distribution in the Jovian system, *Advances in Space Research*, **12**, 337–346, 1992.

Smyth, W. H., and M. R. Combi, A general model for Io's neutral gas clouds. I - Mathematical description, *Astrophysical Journal, Supplement Series*, **66**, 397–411, 1988a.

Smyth, W. H., and M. R. Combi, A general model for Io's neutral gas clouds. II - Application to the sodium cloud, *Astrophysical Journal*, **328**, 888–918, 1988b.

Smyth, W. H., and M. R. Combi, Io's Sodium Corona and Spatially Extended Cloud: A Consistent Flux Speed Distribution, *Icarus*, **126**, 58–77, 1997.

Smyth, W. H., and M. L. Marconi, Io's oxygen source: Determination from ground-based observations and implications for the plasma torus, *Journal of Geophysics Research*, **105**, 7783–7792, 2000.

Smyth, W. H., and M. B. McElroy, The sodium and hydrogen gas clouds of Io, *Planetary Space Science*, **25**, 415–431, 1977.

Smyth, W. H., and M. B. McElroy, Io's sodium cloud - Comparison of models and two-dimensional images, *Astrophysical Journal*, **226**, 336–346, 1978.

Spencer, J. R., and N. M. Schneider, Io on the Eve of the Galileo Mission, *Annual Review of Earth and Planetary Sciences*, **24**, 125–190, 1996.

Spencer, J. R., P. Sartoretti, G. E. Ballester, A. S. McEwen, J. T. Clarke, and M. A. McGrath, Pele plume (Io): Observations with the Hubble Space Telescope, *Geophysics Research Letters*, **24**, 2471, 1997.

Spencer, J. R., K. L. Jessup, M. A. McGrath, G. E. Ballester, and R. Yelle, Discovery of Gaseous S_2 in Io's Pele Plume, *Science*, **288**, 1208–1210, 2000.

Strobel, D. F., X. Zhu, and M. F. Summers, On the vertical thermal structure of Io's atmosphere, *Icarus*, **111**, 18–30, 1994.

Summers, M. E., and D. F. Strobel, Photochemistry and Vertical Transport in Io's Atmosphere and Ionosphere, *Icarus*, **120**, 290–316, 1996.

Summers, M. E., D. F. Strobel, Y. L. Yung, J. T. Trauger, and F. Mills, The structure of Io's thermal corona and implications for atmospheric escape, *Astrophysical Journal*, **343**, 468–480, 1989.

Thomas, N., High resolution spectra of Io's neutral potassium and oxygen clouds., *Astronomy and Astrophysics*, **313**, 306–314, 1996.

Trafton, L., High-resolution spectra of Io's sodium emission, *Astrophysical Journal, Letters to the Editor*, **202**, L107–L112, 1975a.

Trafton, L., Detection of a potassium cloud near Io, *Nature*, **258**, 690–692, 1975b.

Trafton, L., Periodic variations in Io's sodium and potassium clouds, *Astrophysical Journal*, **215**, 960–970, 1977.

Trafton, L., An explanation for the alternating north-south asymmetry of Io's sodium cloud, *Icarus*, **44**, 318–325, 1980.

Trafton, L., and W. Macy, An oscillating asymmetry to Io's sodium emission cloud, *Astrophysical Journal, Letters to the Editor*, **202**, L155–L158, 1975.

Trafton, L., and W. Macy, Io's sodium emission profiles - Variations due to Io's phase and magnetic latitude, *Astrophysical Journal*, **215**, 971–976, 1977.

Trafton, L., T. Parkinson, and W. Macy, The Spatial Extent of Sodium Emission around Io, *Astrophysical Journal, Letters to the Editor*, **190**, L85, 1974.

Vogt, S. S., *UCO/Lick Observatory Tech. Rep. 67, HIRES Users Manual*, 1994.

Wilson, J. K., and N. M. Schneider, Io's fast sodium: Implications for molecular and atomic atmospheric escape, *Icarus*, **111**, 31–44, 1994.

Wilson, J. K., and N. M. Schneider, Io's sodium directional feature: Evidence for ionospheric escape, *Journal of Geophysics Research*, **104**, 16,567–16,584, 1999.

Wolven, B. C., H. W. Moos, K. D. Retherford, P. D. Feldman, D. F. Strobel, W. H. Smyth, and F. L. Roesler, Emission profiles of neutral oxygen and sulfur in Io's exospheric corona, *Journal of Geophysics Research*, **106**, 26,155–26,182, 2001.

Wong, M. C., and W. H. Smyth, Model Calculations for Io's Atmosphere at Eastern and Western Elongations, *Icarus*, **146**, 60–74, 2000.

Zapesochnyi, I. P., and I. S. Aleksakhin, , *Soviet Physics–JETP*, **28**, 41, 1969.