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Hubble Space Telescope

Cycle 13 AR Proposal

The Escape of Oxygen from Mars

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Scientific Category: SOLAR SYSTEM

Scientific Keywords: PLANETARY ATMOSPHERES

Total Budget Amount: $66,000

Abstract

This proposal is to perform detailed analysis of STIS observations of the upper atmosphere of Mars, using an ionospheric model, general circulation model results for the neutral atmosphere, and various recent spacecraft observations of Mars. The end goal is to better understand the escape of oxygen, and by extension water, from Mars. The observations have yielded limb profiles of atomic hydrogen, atomic oxygen, and carbon monoxide with 24 km vertical resolution and a field of view that is thousands of km long. Most of the hydrogen and some of the oxygen atoms thus detected are escaping from Mars. There are no other measurements of volatiles escaping from Mars with nearly such high spatial resolution and large field of view. The data analysis in the original observing proposal will derive spatially-averaged escape rates of hydrogen and possibly oxygen at the time of the observations. This archival research will go beyond that analysis by investigating how the escaping species diffused through the upper atmosphere to reach the exobase and relating these observations of current escape rate to the time history of escape. The escape of water from Mars has had a major impact on its climate history, the understanding of which is a major scientific goal of NASA's Office of Space Science.

Investigators:

	Investigator	Institution	Country
PI	Dr. Jody K. Wilson	Boston University	USA/MA
CoI	Prof. John T. Clarke	Boston University	USA/MA
CoI	Prof. Michael Mendillo	Boston University	USA/MA
CoI	Dr. Paul Withers	Boston University	USA/MA

Number of investigators: 4

Scientific Justification

Atmospheric escape is a major pathway for altering the climate of a planet (e.g. Chamberlain and Hunten, 1987). It occurs on all three of the atmosphere-bearing terrestrial planets (Venus, Earth, Mars). Many of the physical processes leading to atmospheric escape are not well-understood, which impedes our understanding of the past climates of Venus and Mars (Hunten, 1993).

Observations of an elevated deuterium to hydrogen ratio in the martian atmosphere, geological evidence for immense catastrophic flood channels, and integrated surface networks of dendritic drainage and valley systems strongly suggest that Mars once had a much wetter climate (Baker, 2001; Jakosky and Phillips, 2001). This has implications for the accretion of its volatile inventory during the formation of the solar system, its subsequent geological and thermal evolution, and its potential habitability (Jakosky and Phillips, 2001; Owen, 1992). For these and other reasons, understanding the history of water on Mars is a major goal of NASA's Space Science Enterprise (NASA, 2003) endorsed by reports of advisory boards such as COMPLEX, the Office of Space Science's Space Science Advisory Committee, and the National Academy of Science's Solar System Exploration Decadal Survey (COMPLEX, 2001; Belton et al., 2002; SScAC, 2004). "Follow the water" is the guiding theme of NASA's Mars Exploration Program.

The chemical composition and structure of the martian upper atmosphere play major roles in controlling atmospheric escape, and thus focused research into the aeronomy of Mars can help to answer the important and broad-based scientific questions stated above (Hunten et al., 1989). Escape of water from Mars does not take place by the loss of individual water molecules. Instead, these molecules are photo-dissociated in the lower atmosphere and the lighter fragments are transported upwards. The current escape rates of these fragments are balanced such that the net effect is the loss of water molecules (Barth et al. 1992). This maintains the planet's oxidation state. In this proposal we focus on the loss of atomic oxygen as a tracer for water. The most important loss mechanism for neutral atomic oxygen begins with the dissociative recombination of singly-ionized molecular oxygen with an electron, forming two neutral oxygen atoms (Barth et al., 1992; Fox, 1993; Fox and Hac, 1997; Rowe et al., 1993). Some of the energy released in this reaction goes into the kinetic energy of the atoms, which can be sufficient to accelerate the relatively heavy oxygen atom to escape velocity. Note that thermal velocities are not sufficient for appreciable less of oxygen via Jeans escape.

The only significant observations of the martian atmosphere in the ultraviolet from Mars orbit or flyby come from Mariners 6, 7, and 9 over 30 years ago (Barth et al., 1972; Stewart, 1972; Stewart et al., 1972; Strickland et al., 1972; Stewart, 1992). They have poor spatial resolution. By contrast, the recent HST/STIS observations of Clarke's General Observing Proposal 8658 from Aug. 2003 have a spatial resolution of 24 km at Mars and a field of view that is thousands of km long, extending from the center of the disc of Mars to far above its limb. These STIS observations resolve a number of important spectral lines associated with emissions from individual species. There are no other measurements of ultraviolet emission from the martian atmosphere with such high spatial resolution, large field of view, and high spectral resolution.

We will analyse these STIS observations in greater detail than the analysis committed to in Clarke's observing proposal. The STIS observations measure the emission scale heights of atomic hydrogen, atomic oxygen, and carbon monoxide. The oxygen emissions are predominantly from "cold" oxygen with an emission scale height of approximately 170 km. There is evidence in the data for the presence of "hot" oxygen, detectable as an excess brightness over the exponentially decaying "cold " oxygen brightness at the highest altitudes. This identification must be verified by a comparison with models. The preliminary analysis to which Clarke and colleagues are committed by their original observing proposal is to convert these emission scale heights into spatially-averaged number density scale heights and estimate an averaged current escape rate of oxygen from the "hot" oxygen observations by relating them to averaged dissociative recombination rates. The next necessary steps in the analysis, which we propose to do, are to investigate how the escaping species diffused through the upper atmosphere to reach the exobase and relate these observations of current escape rate to the time history of escape. Atmospheric escape may in principle be limited either by the escape flux from the exobase, or, if this flux is large and light atomic species are depleted, by the rate at which new light atoms diffuse upward through the heavier species to the exobase. Analysing these restricted observations in the framework of global models, with sensitivity testing, will provide a better understanding of how atmospheric properties control escape. This analysis may then be applied to the present case and also to prior epochs, when the escape flux is believed to have been much higher. There are no other HST archival data concerning the escape of oxygen from Mars. There have been three HST observations of escaping hydrogen in the context of measuring the D/H ratio, and we will use these observations to test the Mariner 9 discovery of two escaping hydrogen atoms for every escaping oxygen atom (Barth et al., 1992). Carbon monoxide and "cold" oxygen are clearly resolved in the STIS observations. We will infer their number densities in the upper atmosphere and use them in our numerical simulations of escape. Escaping species must diffuse through the rest of the atmosphere to reach the exobase, so the number densities and scale heights of such non-escaping species affects the escape process.

Neutral atomic oxygen also plays an important role in the chemistry of the martian ionosphere (Barth et al., 1992) via its rapid reaction with singly-ionized carbon dioxide. This is the main ion formed by absorption of solar UV radiation by the neutral atmosphere, leading to the formation of singly-ionized molecular oxygen and neutral carbon monoxide. Singly-ionized molecular oxygen formed by this reaction is the dominant ion present in the martian ionosphere. In addition to its involvement in the chemistry of carbon and hydrogen-bearing species, atomic oxygen also influences the chemistry of less-abundant nitrogen-bearing species. These four elements are the building blocks for almost all of the non-inert species in the martian atmosphere and ionosphere (Krasnopolsky, 2002). Our proposed studies of the escape of neutral atomic oxygen from the martian upper atmosphere will also improve our understanding of the planet's ionosphere. Many important atmospheric escape mechanisms are influenced by the state of the ionosphere.

Analysis Plan

We will use an existing Boston University model for simulating the ionosphere of Mars (Martinis et al., 2003), publicly-available results from general circulation models for the neutral atmosphere of Mars (Bougher et al., 2000; Bougher 2004), and spacecraft observations of the martian atmosphere (Withers et al., 2003) to generate synthetic versions of the Clarke HST/STIS observations.

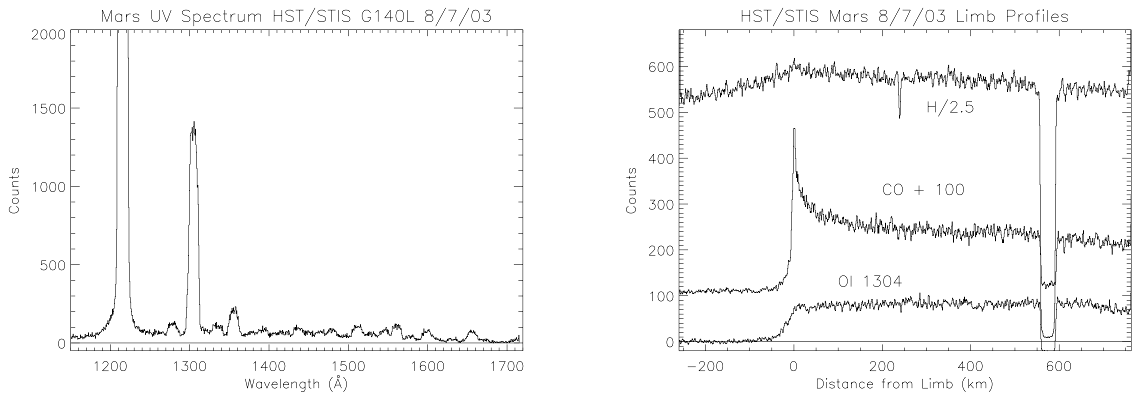

Figure 1: left) STIS spectrum of the Martian airglow showing the high signal-to-noise of the observations we propose to analyse. Emissions from hydrogen (1216 Å), oxygen (1304 Åand 1356 Å), and carbon monoxide (many fainter Cameron bands) are clearly resolved. right) Spatial variation of emissions across the Martian disc and off the limb from STIS long slit spectra. The brightness of each emission line decreases with distance above the limb. Emission from the ("cold") oxygen and carbon monoxide features has a scale height of around a few hundred km, whereas the hydrogen line has a significantly greater scale height, corresponding to greatly elevated temperatures. Positive distances are over the disc of the planet.

Comparison of the brightnesses and emission scale heights of each species will identify those simulations that are broadly consistent with the observations, and more detailed comparisons may also follow. We will identify what scale heights and number densities each atmospheric species must have in order for the simulations to match the observations, then compare these results to other theoretical predictions of atmospheric escape.

The existing HST/STIS observations provide wavelength-resolved profiles of UV emission from the center of the planet to far beyond the limb. Certain atmospheric species, including hydrogen (Lyman alpha at 1216 Angstroms), oxygen (1304 Angstroms and 1356 Angstroms), and carbon monoxide (Cameron bands), are responsible for narrow emission lines in this wavelength region (Figure 1). Emission scale heights derived from these observations can be related to number densities and scale heights of those species in the atmosphere (Figure 2). Initial analysis of these observations shows that two populations of oxygen atoms are probably present, consistent with established theoretical predictions (Fox, 1993; Fox and Hac, 1997). The stronger of these has a relatively small scale height, corresponding to temperatures similar to those of the majority of the atoms in the upper atmosphere, and the weaker, which requires additional analysis before its presence can be definitively confirmed, has a much greater scale height, corresponding to elevated or suprathermal temperatures. These "hot" oxygen atoms are much more likely to escape than the "cold" atoms.

Only hot oxygen atoms formed above the exobase (an altitude of 200 km) can escape from Mars, since such atoms will be rapidly thermalized by collisions if formed below this level. Typical energies of oxygen atoms produced by dissociative recombination are 1–7 eV, comparable to the escape energy of about 2 eV. We will use a simple numerical model to compute the ballistic and

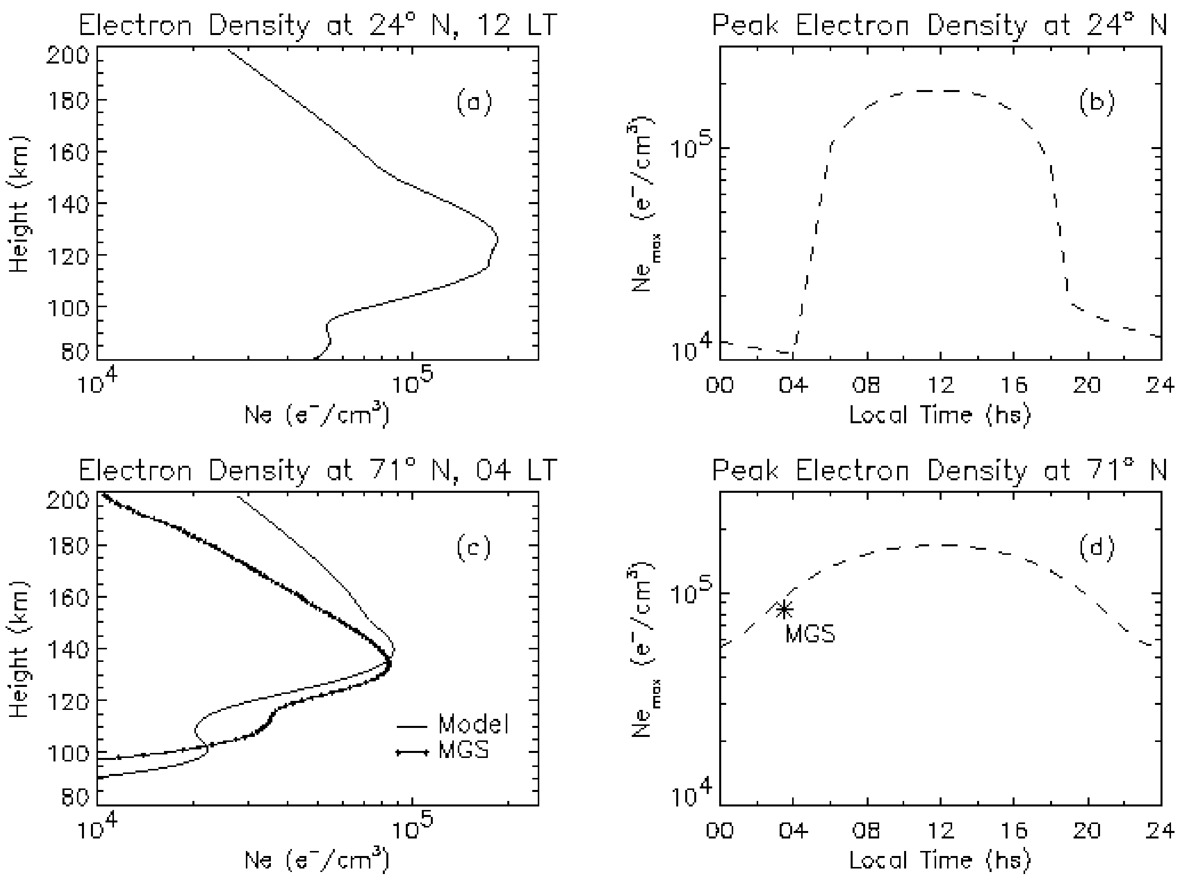

Figure 2: Photochemical model results for the Martian ionosphere in March 1999. (a) Electron density profile for the sub-solar point; (b) diurnal variation of the peak electron density at the sub-solar point; (c) average electron density profile representative of MGS observations: latitude = 71N and local time (LT) = 04 hrs (d) diurnal variation of average peak electron density at 71N. An average profile from the MGS observations is also shown in panel (c) and its peak density in (d). In panel (c) the model does not match the observed ionospheric profile because diffusion has not been included. When diffusion is included, the fit to the observations is good.

escape trajectories of “hot” oxygen atoms and the resulting equilibrium number densities as a function of altitude. The observed emission scale height of hot oxygen atoms below the exobase is controlled by the vertical distribution of their chemical production rate, ultimately driven by the interaction of solar radiation with the neutral upper atmosphere. Above the exobase, it is additionally affected by the outward flow of escaping atoms.

Martinis et al. (2003) describe the development of a model for the martian ionosphere that uses the photochemical interaction of a specified neutral atmosphere and solar flux to generate the number densities of major ionic species as functions of position and time. The five species of ions, all singly-ionized, are carbon dioxide, molecular nitrogen, atomic oxygen, molecular oxygen, and nitric oxide. Solar irradiance values are taken from the Solar2000 model of Tobiska et al. (2000). Co-I Withers has recently added the vertical transport of ions via plasma diffusion to this model. This increases the abundance of ionic species above the altitude of peak photochemical production where timescales for photochemical processes are significantly longer than those for transport by diffusion. The model does not include secondary ionization, magnetic fields, changes to the neutral atmosphere due to chemical or photochemical reactions, or branching reaction paths. The neutral atmosphere does not currently change with latitude, season, or time of day. The model has been validated by comparison of its results to those of more established models (eg Fox and Hac, 1997) and to observations of ionospheric electron densities from the Mars Global Surveyor Radio Science experiment (Bougher et al., 2001; Mendillo et al., 2003). Some results from Martinis et al. (2003) are shown in Figure 3. Ionized hydrogen is not included in the model.

To interpret the HST/STIS data, we will require a model which can predict the amount of emission at a given wavelength, altitude, latitude, longitude, and time of day when a neutral atmospheric structure and incident solar flux are specified. Analysis without such a model, as in Clarke’s original observing proposal, can only give a spatially-averaged impression of the current escape rates at the time and location of the observations. In contrast, the use of numerical simulations alongside observations offers a way to predict escape rates at other latitudes, times of day, and seasons, as well as over an extended period of martian history. For example, are all oxygen or hydrogen atoms that reach the exobase lost from the atmosphere? If so, then the loss of volatiles is set not by the details of any escape mechanism, but by the diffusion of volatiles upwards through the atmosphere. A snap-shot of present escape rates cannot address such a question.

Consequently, the above ionospheric model will be improved to satisfy these requirements. We will improve the model incrementally by incorporating variations in the neutral atmosphere with latitude, longitude, and time of day. The variation of density with altitude of major neutral species at a given latitude, longitude, and time of day can be specified analytically with just a few parameters including base density, homopause altitude, and a temperature profile. Below the homopause, the mixing ratios of neutral species are constant, due to mixing by eddy diffusion, and all species have the same scale height that is set by the local temperature and mean molecular mass. Above the homopause, molecular diffusion dominates and each species has its own scale height that is set by the local temperature and its own molecular mass. Upper atmospheric temperature profiles can be parameterized simply, as discussed in Bates (1959) and Krasnopolsky (2002). Our improved model will be able to specify the neutral atmosphere by means of such parameters and their temporal and spatial variation. We will also track “hot” and “cold” oxygen in the ionospheric model by labelling a certain fraction of oxygen atoms, approximately 60 percent, that are produced by dissociative recombination as "hot" (Fox, 1993; Fox and Hac, 1997). We will continue to validate our developing model by comparison of the results to other models with a well-established history, such as those of Fox and Krasnopolsky.

We will use the results of Krasnopolsky (2002), Bougher (2004), and other workers to define a realistic range of possible neutral atmospheres for use in this ionospheric model. We will also use other spacecraft observations of the martian upper atmosphere in this task. These include measurements of neutral densities and temperatures by aerobraking accelerometer instruments on Mars Global Surveyor and Mars Odyssey (Keating et al., 1998; Withers et al., 2003). They also include measurements of atmospheric temperature that can be derived from the shapes of peaks in electron density in the photochemically-dominated martian ionosphere using Mars Global Surveyor Radio Science experiment results (Bougher et al., 2001; Rishbeth and Garriott, 1969). These datasets are all publicly available on NASA's Planetary Data System and we have worked with them before.

We will use these atmospheric and ionospheric models to simulate the number densities and temperatures of carbon monoxide, and both "hot" and "cold" oxygen for those regions of the atmosphere (latitude, altitude, time of day, and season) which lie within the field of view of the HST/STIS observations. Finally, a simple radiative transfer technique will be used to convert these atmospheric properties into a synthetic HST/STIS observation for detailed comparison with the actual observations. All the emission lines discussed here are optically thin above about 100 km altitude, which simplifies the conversion from number densities to observed emissions.

We will vary parameters in our models to test which values are consistent with the HST/STIS observations. In addition to globally-uniform shifts in a parameter from one simulation to the next, variations in altitude, latitude, longitude, and time of day will be considered. We will test whether our numerical results are sensitive to:

- Variation in bulk neutral density with latitude/longitude/time of day.
- Variation in mixing ratios of neutral species with latitude/longitude/time of day.
- Presence or absence of plasma diffusion in ionospheric model.
- Presence or absence of certain trace neutral or ionized species.
- Variations in parameters describing the neutral temperature profile, such as the constant exospheric temperature that is asymptotically approached as altitude increases.
- Presence or absence or rescaling of certain regions of the solar spectrum.
- Our parameterization of the production of "hot" oxygen in dissociative recombination and variation in this branching ratio with latitude/longitude/time of day.

The implications of these results for the escape of water and other volatiles can then be analysed. In addition to our work, observationally-derived constraints on how such factors affect atmospheric escape can then be used by other workers in more fully-developed models of atmospheric loss to better understand how Mars lost its water.

Relevant Expertise of Personnel

The PI, Jody Wilson, has worked extensively on atmospheric escape on Io, the Moon, and comets. He also led the early development of the BU Mars ionosphere model. Co-I John Clarke has extensive experience in the analysis and interpretation of UV spectra of planetary atmosphere and has led the preliminary analysis of the HST observations we propose to study. Co-I Michael Mendillo is an expert on the terrestrial ionosphere. He has recently begun to apply his skills to the martian ionosphere. Co-I Paul Withers has studied the martian upper atmosphere using a variety of spacecraft observations and he is currently leading the further development and application of the BU Mars ionosphere model.

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Budget Narrative

The majority of the work proposed here will be accomplished by a graduate student, under the day-to-day supervision of PI Wilson and Co-I Clarke, with Co-I Mendillo serving as the student's academic advisor. Regular collaborations and discussions with the other Co-Investigators, who are all at the same institution as the PI, will also take place. We have requested 1 month's salary for Wilson, 1 month's summer salary for Clarke, and 6 month's salary for the graduate student, all including overhead and fringe benefits. The efforts of Mendillo and Withers will be supported by their academic positions and research funds in Boston University's Center for Space Physics at no cost to this proposal. Publication costs and funding for professional travel to scientific conferences are also included in the budget request.

The Astronomy Department and Center for Space Physics have a very talented group of 15 first-year graduate students in the Ph.D. program. Several of these students have expressed interest in joining groups working on planetary science, and so a well-qualified student will be available to help in the work proposed here.

The goals of this proposal will be accomplished by adhering to the following plan of work:

- Modify BU ionospheric model to (a) track hot and cold atomic oxygen and (b) incorporate specification of the number density of neutral species by a few simple parameters and their variation with latitude, longitude, and time of day. Wilson, Withers, and graduate student. 2 months duration.

- Develop radiative transfer techniques for converting results from our numerical models into synthetic HST/STIS spectra. Clarke, Wilson, and graduate student. 2 months duration.

- Explore parameter space in the model to determine what hot oxygen scale heights and number densities are consistent with the HST/STIS observations. Graduate student, supervised by Wilson. 4 months duration.

- Study the implications of these results for escape processes and the role of hot oxygen in the ionosphere. All. 2 months duration.

- Present results at a scientific conference. All. 1 month duration.

- Publish results in the peer-reviewed literature. All. 1 month duration.

Previous Related HST Programs

J. Clarke HST PI Programs (early cycles not listed):

GO 5414 - *Outer Planet H Lyα Auroral/Airglow Line Profiles* (Cycle 3,4): GHRS G160M spectra of Jupiter's northern latitudes show broadening in the H Lyα line wings correlated with H_2 auroral activity and measured H_2 Werner band rotational temperature changes. D. Rego has performed detailed modelling of the expected Lyα line shape with the observed profiles.

"HST/GHRS H_2 Rotational Spectra of Jupiter's Aurora", J. Clarke, L. Ben Jaffel, A. Vidal-Madjar, R. Gladstone, H. Waite, R. Prangé, J.-C. Gérard, J. Ajello, and G. James, *Ap. J. Lett., 430*, L76 (1994)

"Detection of Self-Reversed Lyα Lines from the Jovian Aurorae with the Hubble Space Telescope", R. Prangé, D. Rego, L. Pallier, L. Ben Jaffel, C. Emerich, J. Ajello, J.T. Clarke, and G.E. Ballester, *Ap. J. Lett., 484*, L169 (1997).

"Analysis of the H Lyα emission line profile from Jupiter's aurora", D. Rego, J.T. Clarke, L. Ben Jaffel, G.E. Ballester, R. Prangé, and J. McConnell, *Icarus, 150*, 234 (2001).

GO 6669 - *HST FUV Imaging of Jupiter's Upper Atmosphere Around the Time of the Comet Impact* (Cycle 4-5): Eight orbits of WFPC 2 and FOC far-UV images of Jupiter's upper atmosphere and aurora were obtained during the impacts in cycle 4, and program 6669 was for follow-up observations in cycle 5. The main results are that the impact sites appeared dark in the reflected sunlight over 1800-2100 Å, UV auroral arcs at northern and southern conjugate points appeared tied to the K impact plume, and a varying southern auroral emission preceeded the P2 impact. Analysis work continued at Michigan on a dynamical analysis of the plume images and the evolution of the UV impact sites as a tracer of the dynamics of Jupiter's upper atmosphere, plus an in-depth analysis of the post-K impact auroral features at northern and southern latitudes.

"Hubble Space Telescope Far-Ultraviolet Imaging of Jupiter During the Impacts of Comet Shoemaker-Levy 9", J.T. Clarke, and 20 co-authors, *Science, 267*, 1302 (1995).

"HST Imaging of Jupiter: Atmospheric Phenomena Created by the Impact of Comet S/L 9", H.B. Hammel, and 16 co-authors incl. J.T. Clarke, *Science, 267*, 1288 (1995).

"Auroral Signature of Comet SL9 in the Jovian Magnetosphere", R. Prangé, I. Engle, J.T. Clarke, M. Dunlop, G. Ballester, W. Ip, and J. Trauger, *Science, 267*, 1317 (1995).

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"Ballistic Reconstruction of Ejecta Motion Subsequent to the Impact of S/L 9 Fragments A and G with Jupiter", K.L. Jessup, J.T. Clarke, G.E. Ballester, and H.B. Hammel, *Icarus, 146*, 19 (2000).

GO 5828, 6743, 7308, 8171, 8657 - *HST Far-UV Imaging and Spectra of Jupiter's Aurora* (Cycles 5-9): This program is to obtain UV images and spectra of Jupiter's aurora. Observations were initially made during the Galileo orbiter in situ measurements of Jupiter's particles and fields and night side aurora, and a cycle 9 campaign has been conducted in parallel with Cassini measurements of the solar wind approaching Jupiter and night side observations. The most recent papers published in *Nature* present STIS spectra and images of the aurora, compared with Cassini and Galileo *in situ* measurements.

"Far-UV Imaging of Jupiter's Aurora with HST/WFPC 2", J.T. Clarke and 20 co-authors, *Science, 274*, 404 (1996).

"Time-Resolved Observations of Jupiter's Far-UV Aurora: Comparison of WFPC2 and IUE", G.E. Ballester, J.T. Clarke, and 20 co-authors, *Science, 274*, 409 (1996).

"HST Imaging of Jupiter's UV Aurora During the Galileo Orbiter Mission", J.T. Clarke and 10 co-authors, *J. Geophys. Res., 103*, no. E9, 20,217 (1998).

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"Ultraviolet Auroral Emissions from the Magnetic Footprints of Io, Ganymede, and Europa on Jupiter", J.T. Clarke, J. Ajello, G. Ballester, L. Ben Jaffel, J. Connerney, J.C. Gérard, R. Gladstone, D. Grodent, W. Pryor, J. Trauger, and H. Waite, *Nature, 415*, 997 (2002).

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"Jupiter's Main Auroral Oval Observed with HST-STIS", D. Grodent, J. Clarke, J. Kim, H. Waite, and S. Cowley, *J. Geophys. Res., 108*, A11, 1389, doi:10.1029/ 2003JA009921 (2003).

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"A Possible Auroral Signature of a Sub-Storm-like Process on Jupiter", D. Grodent, J.-C. Gérard, J. Clarke, R. Gladstone, and H. Waite, submitted to *J. Geophys. Res.* (2003).

DD 10083 - *HST UV Images of Saturn's Aurora Coordinated with Cassini Solar Wind Measurements*, (Cycle 12): This program is for 17 orbits of STIS UV imaging of Saturn's aurora coordinated with continuous Cassini measurements of the solar wind approaching Saturn in Jan. 2004. The initial images are just being collected as this proposal is being written.

Cycles 5-6 GTO (as Co-I with John Trauger PI): GTO 5217 - *Jupiter's Aurora and Airglow* GTO 5219, 6215 - *Saturn's Aurora, Airglow, and Extended Atmosphere* These programs average 4-6 hours each, taking far-UV images of the outer planets with the WFPC 2 / F160BW. The aurora/albedo images of Jupiter and Saturn have been highly successful. Saturn UV imaging continued into cycle 6 as GTO programs and the Saturn auroral images have been published in *J.G.R.*.

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GO 8117 (as Co-I with John Trauger PI): This program is to obtain images and mainly spectra of Saturn's UV auroral emissions, disc, and the polar cap hazes surrounding the southern pole. The observations were conducted in Jan. 2001, and are presently being analyzed. The main emphasis in this program is the study of the effects of the auroral energy in producing the absorbing polar cap aerosols, their distribution and dynamics, and their composition.