Project Summary
AGS-PRF: To What Extent are Jupiter's Magnetosphere and Aurora Influenced by the Solar Wind?

Proposed Sponsoring Scientist: Professor Paul Withers
Proposed Host Institution: Boston University

Overview

The nature of the solar wind interaction with Jupiter's magnetosphere and aurora is an area of active research and debate, due in part to the lack of available solar wind measurements near Jupiter's orbit. Because of the rapid planetary rotation and large spatial scales in Jupiter's magnetosphere, it is thought that centrifugal stresses may play a significant role in driving magnetospheric dynamics and that the solar wind may have a relatively minor effect. The proposed study will use a model of the solar wind properties propagated outward from 1 AU to estimate the solar wind conditions near Jupiter. The proposed work includes analysis of *in situ* magnetic field and particle data, and HST images of Jupiter's aurora, to investigate whether temporal changes in these data may be statistically associated with changes in the modeled solar wind properties.

Intellectual Merit

The proposed work will investigate the solar wind interaction with Jupiter's magnetosphere and aurora by using an MHD model of the propagated solar wind conditions to overcome the lack of upstream monitoring at the outer planets. The results will show whether there is evidence that the solar wind drives tail reconnection at Jupiter and Saturn, and will qualitatively and quantitatively describe how Jupiter's magnetosphere and aurora respond to changing solar wind conditions. The work will address whether quasi-periodic behavior observed in Jupiter's magnetosphere may be controlled by the solar wind. This study will also determine how Jupiter's main auroral emission responds to changing solar wind conditions, and compare findings to theories and models. The results of the study will contribute generally to the understanding of the fundamental physical processes involved in solar wind-magnetosphere coupling. It will provide an important step toward understanding the relative roles of the solar wind and internal factors in driving tail reconnection in giant planet magnetospheres. Comparative planetary studies such as the work proposed here are a useful, new approach to improve the present understanding of the Sun-Earth connection.

Broader impacts

Boston University provides several education and public outreach activities through which the proposed research can be shared with the university and local community. For example, BU's Department of Astronomy hosts a weekly public open night at their campus observatory in central Boston. Results from the proposed research and other recent advances in space plasma physics will be presented to the public during these open nights while groups are waiting to use the telescopes. Additionally, BU's G-WISE (Graduate Women in Science and Engineering) organization provides an opportunity to mentor graduate students. In addition to these activities, the results of the proposed research will be shared through talks at scientific conferences and publications. Effort will also be spent to maintain and update an online web form and existing IDL software that disseminate the results of an existing Jovian magnetosphere/ionosphere mapping model [*Vogt et al*, 2011]. This model has been used by the scientific community in interpreting auroral images from HST and in preparation for the Juno mission.

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AGS-PRF: To What Extent are Jupiter's Magnetosphere and Aurora Influenced by the Solar Wind?

1. Introduction

The gas giant planet Jupiter possesses a strong internal magnetic field that deflects the plasma flowing in the solar wind, forming a magnetosphere. In both absolute and relative (to the planetary radius) terms, Jupiter's magnetosphere, illustrated in **Figure 1**, is the largest in the solar system, with a typical magnetopause standoff distance of ~60-90 R_J depending on the solar wind dynamic pressure. These large spatial scales and a rapid planetary rotation period (~10 hours) contribute to the importance of centrifugal stresses in Jupiter's magnetosphere. The magnetospheric plasma primarily comes from the volcanically active moon Io, rather than from the solar wind as at Earth, and is comprised of sulfur and oxygen ions. These features make Jupiter a unique and exciting target for studies of the coupling between the solar wind and a planetary magnetosphere.

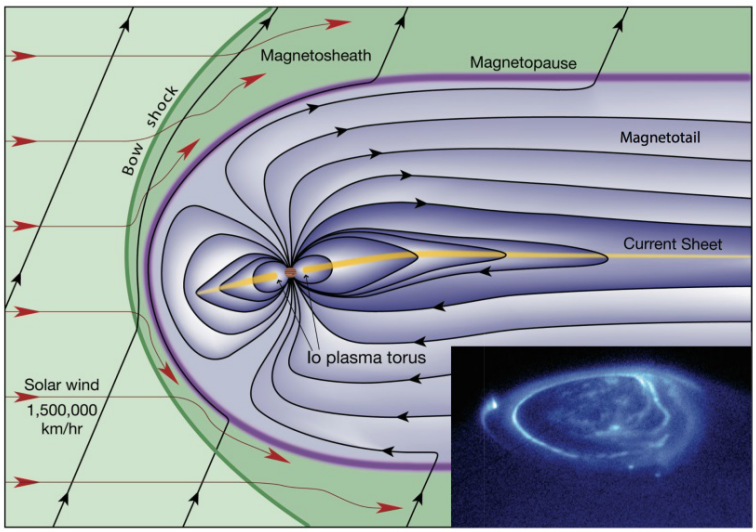

Figure 1. The main features of Jupiter's magnetosphere, shown here in a meridional plane, including the Io plasma torus, current sheet, and stretched field configuration. Arrows indicate the magnetic field direction. **Inset:** HST image of Jupiter's UV aurora (J. Clarke/NASA), including the main emission and satellite footprints. *Modified from F. Bagenal and S. Bartlett.*

It is commonly assumed that Jupiter's magnetospheric dynamics are internally rather than solar wind driven [e.g. *Vasyliūnas*, 1983; *Krupp et al.*, 2004, and references therein], though the extent to which the solar wind influences the magnetosphere is still under debate [e.g. *McComas and Bagenal,* 2007; *Cowley et al.*, 2008; *Delamere and Bagenal*, 2010]. Although magnetic field and particle data from Jupiter's magnetosphere are available from eight spacecraft missions, in most cases only single-spacecraft measurements are available, making it difficult to obtain information about the upstream solar wind conditions. One exception is the Cassini flyby interval in 2000, when the Galileo orbiter was located in Jupiter's magnetosphere and Cassini was located in the upstream solar wind. Data from this interval show that Jupiter's magnetosphere and aurora evince a measurable response to the passage of an interplanetary shock in the solar wind [e.g. *Gurnett et al.*, 2002; *Hanlon et al.,* 2004; *Nichols et al.,* 2007], but are too limited to be of use in statistical studies. **Consequently, many important questions regarding how the solar wind interacts with Jupiter's magnetosphere and aurora remain to be answered.** We propose to answer two of the most fundamental of these questions:

- ***How do Jupiter's magnetosphere and aurora respond to changing solar wind conditions?***
- ***Does the solar wind drive, or otherwise influence, tail reconnection at Jupiter?***

In order to address these questions, we will combine in situ magnetospheric data from the Galileo spacecraft and UV observations of Jupiter's aurora from the Hubble Space Telescope (HST). We shall resolve the problem of poorly-constrained upstream solar wind conditions,

which has plagued previous work in this area, by predicting the solar wind conditions upstream of Jupiter with a magnetohydrodynamic (MHD) model that can propagate observations made at 1 AU outward to Jupiter's orbit at 5.2 AU. We will test whether temporal changes to the Jovian magnetic field, particle, and auroral radio emission observations may be statistically associated with changes in the upstream solar wind model data. **The proposed work will include more magnetospheric datasets, combined auroral and magnetospheric observations, and a much larger sample size than previous studies.**

We propose to study the interaction between Jupiter's magnetosphere and the solar wind, not only to advance our knowledge of this system, but also to inform studies of the analogous interaction at the Earth. For example, better understanding of the solar wind's role in tail reconnection and plasma transport at Jupiter can also inform studies of the plasma injections associated with substorms in the Earth's magnetosphere. Establishing how Jupiter's magnetosphere responds to changing solar wind conditions contributes generally to our knowledge of the fundamental physical processes involved in magnetic storms and in solar wind-magnetosphere coupling, which are objectives of NSF's Magnetospheric Physics and Geospace Environment Modeling (GEM) programs. Finally, the results will be directly applicable to other rotation-dominated systems, such as Saturn, whose magnetosphere also features an internal plasma source.

2. Scientific Background / Previous Work

2.1 Jovian magnetospheric dynamics: *internal vs. solar wind driving*

Magnetic reconnection is an important physical process that allows for the release of built-up of mass and energy from a magnetosphere. The mechanism by which magnetic reconnection occurs is a critical diagnostic of the overall behavior of a magnetosphere. In the Earth's magnetosphere, the solar wind is the primary plasma source, and magnetotail reconnection is driven by the solar wind, in a process called the Dungey cycle [*Dungey*, 1961]. By comparison, at Jupiter, it has been proposed that centrifugal stresses, rather than the solar wind, may be the dominant factor driving magnetospheric dynamics. For example, one can consider the ratio of the potential energy from corotation to the solar wind induced potential across the polar cap (the latter being an indicator of the amount of energy available from the solar wind). This ratio is about 5 for the Earth and about 50 for Jupiter, suggesting that rotational stresses are much more significant than the solar wind in driving dynamics at Jupiter [*Khurana et al.*, 2004]. The proposed internally-driven tail reconnection process is known as the Vasyliunas cycle [*Vasyliūnas*, 1983]. It occurs as mass-loaded flux tubes rotate into the night side, are stretched radially by the centrifugal force, break off, and release a plasmoid, as illustrated in **Figure 2**.

Multiple magnetospheric datasets collected by the Galileo spacecraft, which orbited Jupiter from late 1995 to 2003, have shown evidence of reconnection in Jupiter's magnetotail [e.g., *Russell et al.*, 1998; *Kronberg et al.*, 2005; *Vogt et al.*, 2010]. The observed reconnection

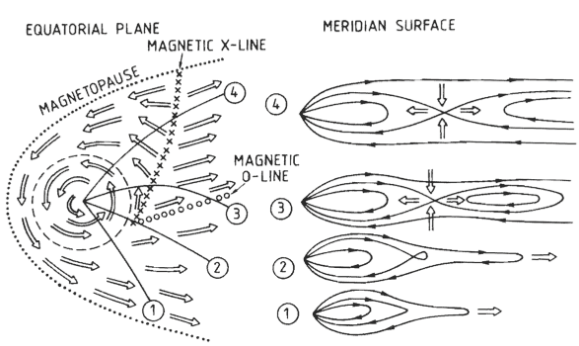

Figure 2. Schematic of the internally driven reconnection of the Vasyliunas cycle. Mass-loaded flux tubes (1) rotate to the night side, (2) are stretched due to centrifugal acceleration of rotating particles, and (3-4) pinch off, releasing a plasmoid. *From Vasyliūnas* [1983].

signatures include flow bursts measured by the Galileo Energetic Particle Detector (EPD) [*Woch et al.*, 1998; *Kronberg et al.*, 2005, 2008] and magnetic field dipolarizations and reversals measured by the magnetometer [*Vogt et al.*, 2010]. These events have also been associated with increases in the hectometric (HOM) auroral radio emissions, measured by Galileo's Plasma Wave Subsystem (PWS) [*Louarn et al.*, 1998, 2000, 2007]. Jupiter's auroral radio emissions are generated by the cyclotron maser instability, analogous to the observed auroral kilometric radiation (AKR) at the Earth and the Saturn kilometric radiation (SKR), and extend in frequency from the kilometer to decimeter range. The HOM emissions have frequencies between a few hundred kHz and a few MHz and originate in the high-latitude auroral zones [*Zarka*, 1998]. **Figure 3** shows an example of these reconnection signatures in the Galileo data.

As **Figure 3** shows, Jupiter's magnetosphere displays quasi-periodic variations, typically on ~2-3 day timescales, that are similar to the expected characteristic time scale of an internally-driven mass loading and release process associated with the Vasyliunas cycle [*Kronberg et al.*, 2007]. However, the behavior of the magnetosphere is more stochastic than would be expected for a pure, idealized Vasyliunas cycle. For example, magnetospheric conditions are exceptionally dynamic during brief intervals (for example, Galileo orbits G2 and G8) but relatively quiet at other times. **An important unanswered question is whether these dynamic intervals resulted from external conditions, such as the solar wind, or whether these spacecraft orbits passed through a particularly dynamic region of the magnetosphere.** Additionally, the ~2-3 day quasi-periodic behavior occurs only intermittently, particularly in the magnetic field data, and the characteristic period can vary from 1 to 7 days [*Kronberg et al.*, 2009]. **A major outstanding question is why this quasi-periodic behavior is not always observed, and why the characteristic period varies from 1 to 7 days [*Kronberg et al.*, 2009].**

We will address these questions by testing the idea that variability in the magnetospheric state and characteristic period could be driven by variations in the external solar wind conditions. In MHD simulations of the magnetospheres of both Jupiter and Saturn (another large, rapidly rotating magnetosphere), the characteristic time scales for periodic plasmoid release vary with solar wind conditions [e.g., *Fukazawa*, 2005; *Fukazawa et al.*, 2006, 2010; *Zieger et al.*, 2010; *Jia et al.*, 2012]. Alternately, the variability could be linked to changes in the rate at which Io adds plasma to the magnetosphere, though this quantity is difficult to measure. Therefore, we will focus on the competing hypothesis that the solar wind influences, or even drives, dynamics at Jupiter.

2.2 Solar wind influence on Jupiter's magnetosphere and aurora: Data and models

Much of our present knowledge of the interaction between Jupiter's magnetosphere and the solar wind comes from the Cassini flyby of Jupiter in December 2000-January 2001, when the approaching Cassini spacecraft served as an upstream solar wind monitor while Galileo made in situ measurements of magnetospheric conditions. **Observations from this interval show that Jupiter's magnetosphere and the UV aurora are influenced by changing solar wind conditions.** For example, following the arrival of an interplanetary shock at Jupiter, the magnitude of the magnetic field in the magnetosphere and the intensity of HOM auroral emissions increased [*Gurnett et al.*, 2002; *Hanlon et al.*, 2004]. The plasma azimuthal velocity also increased, consistent with conservation of angular momentum as the magnetosphere becomes compressed and plasma moves inward. These observations established that Jupiter's magnetosphere is not solely controlled by internal processes, such as those associated with the planet's rotation or Io's activity.

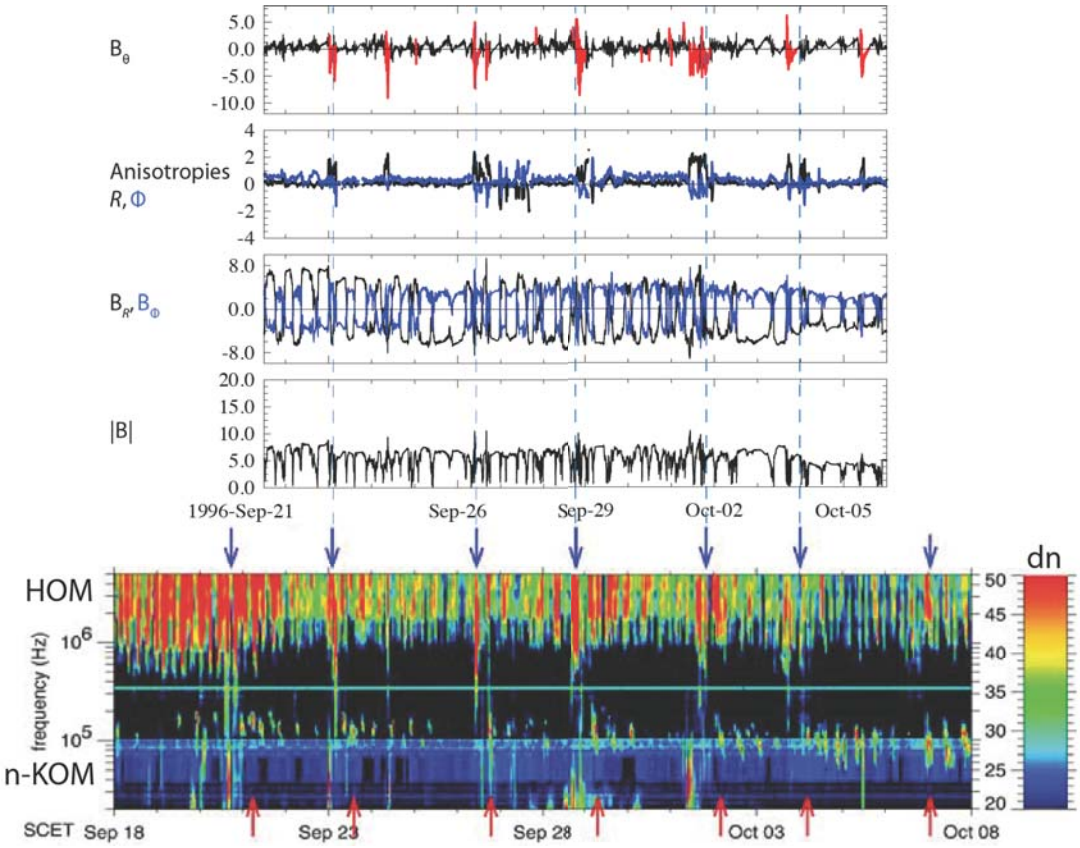

Figure 3. Examples of the characteristic 2-3 day periodicity observed in Jupiter's magnetosphere, shown on the same time scale for an interval during Galileo orbit G2 in September-October 1996. **(Top)** Magnetic field and flow anisotropies as a function of time. Reconnection signatures (red highlighted intervals in B_θ, the north-south magnetic field component) and radial flow bursts (indicated by increased radial anisotropy) measured by the Energetic Particle Detector show good agreement. *Modified from Vogt et al.* [2010]. **(Bottom)** Frequency-time spectrogram of Jupiter's radio emissions in the hectometric and kilometric frequency ranges, measured by Galileo's Plasma Wave Subsystem. The HOM intensity increases every 2-3 days (blue arrows and vertical dashed lines), in good agreement with the EPD and MAG reconnection signatures. *Modified from Louarn et al.* [2007].

Other studies of Jupiter's interaction with the solar wind have relied on MHD models of the solar wind data propagated out to Jupiter from 1 AU. For example, *Tao et al.* [2005] developed a 1-D MHD model of the propagated solar wind conditions for comparison to the in situ magnetic field data collected by Galileo. They found that most intervals with a large (> 0.25 nPa) modeled solar wind dynamic pressure were accompanied by magnetospheric changes such as compression of Jupiter's magnetic field or a current sheet displacement. These past studies generally used only one magnetospheric dataset or a subset of the Galileo orbits. **Our proposed work will expand on previous studies by using multiple datasets from many Galileo orbits.**

Jupiter's auroral emissions, shown in **Figure 1**, provide an excellent way to remotely sense the varied physical processes occurring in Jupiter's magnetosphere. Jupiter's main auroral emission is associated with corotation enforcement currents which arise near radial distances of ~30 R_J in the middle magnetosphere as outward-moving plasma decelerates to conserve its angular momentum [*Hill*, 2001; *Cowley and Bunce*, 2001]. Thus, at Jupiter, the main influences

on the position and brightness of the main auroral emissions are internal factors like mass loading and the planet's rotation, whereas at Earth the primary influence on auroral activity is the solar wind. However, theoretical models predict that both the brightness and position of Jupiter's main emission should respond to a change in the solar wind dynamic pressure. For example, as the magnetosphere is compressed, plasma would move inward and accelerate, reducing the need for the corotation enforcement currents that drive the main emission [*Cowley and Bunce*, 2001; *Southwood and Kivelson*, 2001].

Hubble Space Telescope observations of Jupiter's UV auroral emissions during the Cassini flyby interval showed that the auroral emissions brightened by a factor of ~2 during a period of changing solar wind dynamic pressure [*Nichols et al.*, 2007]. However, timing uncertainties in propagating the solar wind from Cassini to Jupiter made it difficult to determine whether the brightening was associated with the high or low solar wind dynamic pressure intervals. **In the proposed work, we will combine auroral observations with in situ magnetospheric data to support the interpretation of many existing HST auroral images from the Galileo era and establish the influence of the solar wind on Jupiter's auroral emissions.** We will ameliorate the problem of the lack of upstream solar wind data by using model predictions of solar wind conditions at Jupiter. A major weakness of propagated solar wind models is that they predict the correct solar wind conditions at Jupiter, but with timing uncertainties as long as tens of hours (Section 3.2). However, if the response of in situ magnetic field and particle measurements in Jupiter's magnetosphere to disturbed solar wind conditions can be established, then timing errors in model predictions can be reduced by using in situ data as a diagnostic tool to infer the magnetospheric state and therefore the upstream solar wind conditions.

3. Technical Approach and Methodology

3.1 Proposed Research

We propose to study the interaction between the solar wind and Jupiter's magnetosphere and aurora by comparing magnetospheric observations to the upstream solar wind conditions inferred from a propagated solar wind model called mSWiM. Details on this model are provided in section 3.2. In comparison to previous studies that also used propagated solar wind models, our work will consider additional data sets over a larger time interval. For example, *Tao et al.* [2005] only considered magnetic field data, and only from four Galileo orbits, though *in situ* data are available from at least 20 additional orbits, including 5 orbits (G2, G8, E17, I24, and I25) that occurred within 75 days of apparent opposition, when mSWiM's prediction efficiency is highest. Additionally, no one has yet studied whether there may be a link between the solar wind conditions and the observed Jovian reconnection events or the intermittent 2-3 day periodicity.

The proposed research is comprised of three tasks. **In the first task** we will survey the available *in situ* Galileo data, including magnetometer data, energetic particle data, and HOM auroral radio emissions, to examine the response of each quantity to solar wind events, particularly intervals of high dynamic pressure or an interplanetary shock. Changes in the magnetospheric magnetic field components reveal reconnection signatures [e.g. *Vogt et al.*, 2010] and the magnetic field magnitude can indicate whether the magnetosphere is in a compressed or expanded state. The EPD data can be used to infer changes to the plasma azimuthal flow, which is important for understanding changes in the main auroral emission, and flow bursts that are indicative of reconnection [e.g. *Hanlon et al.*, 2004; *Kronberg et al.*, 2005]. Increases in the power of the HOM auroral radio emissions are interpreted as signatures of

magnetospheric energy release on a global scale [e.g. *Louarn et al.*, 2007, 2014]. Both the EPD data and HOM emissions can be used to infer information about the plasma sheet thickness and radial plasma transport. The solar wind conditions will be predicted by a propagated solar wind model called mSWiM that is described in section 3.2.

It will be crucial to compare upstream solar wind conditions during intervals when the Galileo spacecraft passed through similar regions of the magnetosphere, to address the difficulty in separating spatial and temporal effects due to the nature of single-spacecraft measurements. The inbound portions of orbits G8 (which was highly dynamic, see **Figure 4**) and C9 (which was not as dynamic) were nearly collocated and are good candidates for comparison.

Where possible, we will use quantitative criteria to define events or intervals of interest in each data set. In our analyses of magnetospheric responses and solar wind drivers, we will apply statistical tests, such as calculating correlation coefficients and performing event association tests, where appropriate. Event association tests are similar to a cross-correlation, but are calculated for event timings, and have been used to investigate the causal relationship between northward IMF turnings and substorm onsets in the Earth's magnetosphere [*Hsu and McPherron*, 2002]. These tests can be used in our work to compare the predicted interplanetary shock arrivals to magnetospheric events such as local magnetic field compressions, the 249 reconnection events identified in Galileo magnetometer data by *Vogt et al.* [2010], increases in the HOM auroral radio emissions, and changes in the plasma flows as measured by the EPD.

As part of our preliminary analysis we have identified ~70 Jovian magnetic field compressions by eye and find that roughly two thirds of these are accompanied by an increase in the predicted solar wind dynamic pressure, P_{Dyn}. For example, blue arrows in the |B| panel (bottom) of **Figure 4** show two events in which Jupiter's magnetosphere is compressed, as

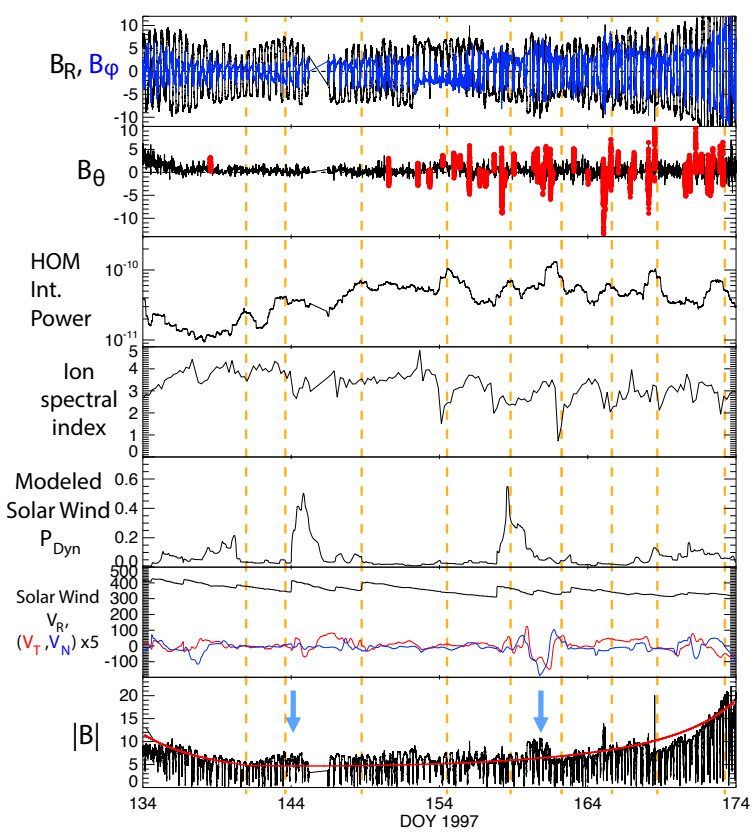

Figure 4. Parameters plotted as functions of time during Galileo orbit G8, from top to bottom: measured magnetic field components, integrated power of HOM auroral radio emissions, ion spectral index γ, predicted properties of the solar wind (dynamic pressure, velocity), and finally the observed magnetospheric magnetic field magnitude. The ion spectral index γ is the slope of the energy spectrum from the Galileo EPD; changes in γ correspond to changes in the plasma sheet thickness. Quasi-periodic changes in the HOM power agree with changes in the ion spectral index γ (orange vertical lines). Red highlighted intervals in the B_θ panel show reconnection events identified by *Vogt et al.* [2010]. Blue arrows correspond to magnetospheric compression events (see text).

evidenced by a transient increase in the field magnitude over background levels (red line). These compression events occur close to predicted times of increased predicted P_{Dyn}, indicating that the mSWiM model can accurately predict solar wind arrival times at Jupiter.

Future work will include developing an automated procedure to identify these events and then performing statistical tests. We will also test the hypothesis that the solar wind controls or otherwise influences the 2-3 day periodicity in Jupiter's magnetosphere by comparing periodic behavior of various solar wind properties to periodic signals in the in situ data. For example, **Figure 4** shows a clear ~2-3 day periodic behavior in several magnetospheric datasets (orange dashed lines), though there is no evidence of this periodicity in the modeled solar wind properties. We will initially identify periodic signals through visual inspection, as has been done in previous studies [e.g. *Kronberg et al.*, 2009], though where appropriate, we will compute periodograms and determine statistical significances. Analysis will be performed both on the data set as a whole and individually for each Galileo orbit (~30 day intervals), since the periodicity in Jupiter's magnetosphere is intermittent and the characteristic time scale varies.

The second task will study the response of Jupiter's aurora to changing solar wind conditions. Specifically, we will analyze HST images from the Galileo era to establish how the position and brightness of the main auroral emission change in response to high solar wind P_{Dyn} events and interpret these changes in the context of the observed changes in the plasma azimuthal velocity and the inferred changes to the corotation enforcement current system. Ours will be the first study to use the in situ magnetic field and particle measurements from Galileo as a diagnostic tool to identify the state of Jupiter's magnetosphere for comparison to contemporaneous HST images. From the first task, we will have established the magnetospheric response to a solar wind compression or rarefaction. Therefore we can reduce the timing errors associated with the mSWiM model by using *in situ* data as a diagnostic tool to infer the magnetospheric state and therefore the upstream solar wind conditions.

HST observations with concurrent *in situ* Galileo measurements are available on at least 8 dates from 1997 to 1999, including 5 dates close to opposition, when mSWiM's prediction efficiency is highest. Another 7 days of HST observations from the Cassini flyby interval have been previously analyzed by *Nichols et al.* [2007]. Sample HST observations from the Galileo era, illustrating changes in the main emission brightness and position, are shown in **Figure 6**.

For each day with HST images, we will use concurrent magnetospheric observations to predict how the position and brightness of the main auroral may differ from the nominal state, then compare these predictions to the HST observations. Our predictions will be based on the predicted solar wind conditions and on observed changes in the azimuthal plasma flows. The magnetic field data (through the field bend back) and EPD data (through measured particle anisotropies) can provide information on azimuthal plasma flows, and therefore the radial position where corotation breaks down in the magnetosphere (where the main auroral emission is expected to map). Our analysis will test theoretical predictions of links between magnetospheric and auroral properties [e.g. *Cowley and Bunce*, 2001, 2003a, 2003b] and can also be used to test theories and modeling results [e.g. *Chané et al.*, 2013] regarding the effects of the solar wind on Jupiter's main emission brightness and position.

In our analysis we will also study transient auroral features like flares [e.g. *Waite et al.*, 2001] and polar dawn spots, which are thought to be associated with inward moving flow from tail reconnection [e.g. *Radioti et al.*, 2010, 2011]. We will explore how the occurrence and other properties, like ionospheric position and brightness, are influenced by changes in solar wind conditions. Understanding how these additional auroral features are influenced by the solar wind

provides a great amount of insight into the global response of Jupiter's magnetosphere to changing solar wind conditions, as auroral images provide remote sensing proxy of the entire magnetosphere, whereas in situ measurements are limited to a single position.

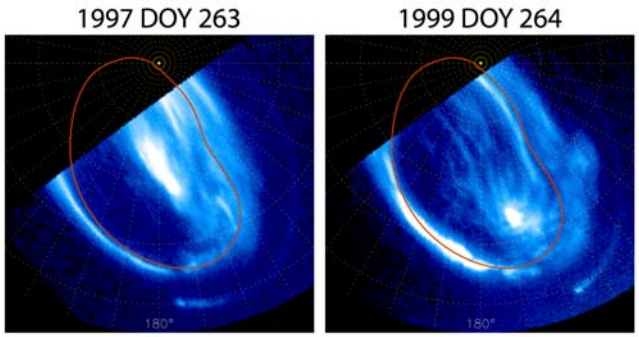

Figure 6. Example HST auroral observations from the Galileo era, at times with available in situ magnetic field and particle data. The main emission in the right image is more poleward, brighter, and broader, than in the left image. The red line shows a statistical location for the main emission from *Nichols et al.* [2009].

Finally, **in our third task** we will extend our study to Saturn and analyze the solar wind conditions during and prior to intervals of tail reconnection to search for evidence of solar wind driving. Saturn, like Jupiter, is a rapid rotator, and its magnetosphere is characterized by large spatial scales and an internal plasma source (primarily the moon Enceladus). Therefore it is likely that tail reconnection is at least partially driven by centrifugal stresses and the Vasyliunas cycle [e.g., *Cowley et al.*, 2005], though there is also observational evidence that the solar wind influences the amount of open flux in Saturn's polar cap [e.g., *Badman et al.*, 2005] and could drive tail reconnection. At Saturn, as at Jupiter, the absence of an upstream solar wind monitor makes it difficult to assess the role of the solar wind in driving magnetospheric dynamics. Therefore, we propose to use these previously-identified events and the mSWiM model to perform an analysis similar to that proposed for the Jovian reconnection events, but for the nearly 100 tail reconnection signatures that have been identified in Cassini magnetometer data [*Jackman et al.*, 2011, 2014]. We will determine whether tail reconnection at Saturn occurs preferentially under certain solar wind conditions, employing statistical association tests as with the proposed Jovian study. The results would provide a significant step forward to understanding what drives dynamics in giant planet magnetospheres.

3.2 The Michigan propagated solar wind model (mSWiM)

In order to estimate the solar wind conditions upstream of Jupiter, we propose to use the Michigan Solar Wind Model, known as mSWiM. It is a 1-D MHD model that propagates solar wind data, obtained from the OMNIWeb database at http://omniweb.gsfc.nasa.gov/, from the Earth's orbit at 1 AU to as far out as 10 AU. The model has been widely used to estimate the solar wind conditions upstream of Jupiter and Saturn in studies of the outer planet magnetospheres and aurorae [e.g. *Clarke et al.*, 2009; *Ebert et al.*, 2010; *Hess et al.*, 2012]. Complete details about the model, its assumptions, and its statistical validation are provided in *Zieger and Hansen* [2008] and on the mSWiM website, http://mswim.engin.umich.edu/.

Model data are publicly available for download from the mSWiM website for both Jupiter (~5.2 AU) and Saturn (~9.5 AU). Model outputs include the solar wind density and temperature, and interplanetary magnetic field (IMF) and solar wind velocity components in RTN coordinates. These quantities are provided with a typical time resolution of a few minutes and are available nearly continuously from 1994 to 2008, which is ideal for comparison with the *in situ* data from Galileo. **Figure 7** compares the modeled solar wind properties to observations from Pioneer 10 and shows generally good agreement.

As with any model, mSWiM is subject to error and has limitations that must be taken into account during use. For example, the model's prediction efficiency is highest within 75 days of apparent opposition and at times with a high recurrence index in the solar wind speed. The expected error in shock arrival time is as small as 10-15 hours for high recurrence index, and ~35 hours for a low recurrence index. Additionally, some quantities such as the solar wind speed and density are predicted better than others. While it is important to acknowledge model limitations, we expect that some of the errors will average out in our analysis, as we will compare model solar wind conditions to hundreds of reconnection events and local Jovian field compressions.

To further account for possible timing errors in the mSWiM model, we will include the propagated solar wind model results of *Tao et al.* [2005] in our analysis. We can have higher confidence in the predicted upstream solar wind conditions for intervals in which the two models agree. Model data from *Tao et al.* [2005] are also publicly available for download, though the available output is limited to the solar wind density, radial velocity, and dynamic pressure.

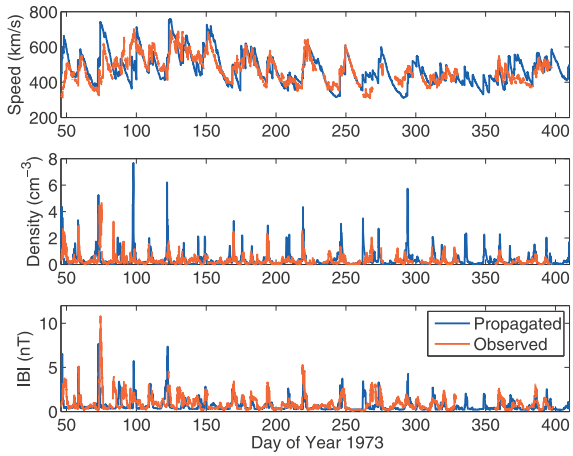

Figure 7. Predictions (blue) from the mSWiM model compared to Pioneer 10 observations at ~3.6-5 AU (red). The modeled solar wind properties (from top: speed, density, and magnetic field magnitude) show good agreement with the observations in both timing and amplitude. *Modified from Zieger and Hansen [2008], figure 5.*

4. Justification for carrying out research at Boston University

Boston University is a leading institution in the field of planetary space physics and its Department of Astronomy is home to several faculty and research staff with expertise that is directly relevant to my proposed research. In particular, Dr. Bertalan Zieger, who developed the propagated solar wind model that will be used in my proposed research, and Prof. John Clarke, an expert on the aurorae of Jupiter and Saturn, are both part of BU's Center for Space Physics. Prof. Clarke's work has included studies of the solar wind influence on the UV aurora at Jupiter and Saturn as seen by HST. Prof. Theodore Fritz, who has worked with energetic particle data from the Galileo spacecraft, also works at BU. My host at BU will be Prof. Paul Withers, who has studied the solar wind-magnetosphere interaction at Mars.

BU is located in close proximity to MIT, Harvard, and the University of New Hampshire, which are all home to active research on the solar wind and planetary magnetospheres. This proximity will allow me to build collaborations with individuals at these institutions.

Standard computing resources for academic scientists will be provided by Boston University for all Boston University personnel involved in this project. Standard office facilities will be provided by Boston University for the proposed activities.

5. Long term career goals

This postdoctoral fellowship will be an excellent step toward achieving my long-term career goal of becoming a university faculty member. My research interests are in planetary space physics,

specifically in understanding how different planetary environments affect magnetospheric dynamics and aurora. My Ph.D. work was comprised of studies regarding Jupiter's magnetospheric structure and dynamics, including analysis of Galileo magnetometer and EPD data and modeling. The proposed work at BU would be a natural extension of my dissertation research that would give me an opportunity to work with new data sets, including images from the Hubble Space Telescope, and to extend my expertise to Saturn.

6. Significance of proposed work

6.1 Intellectual Merit

The proposed work will investigate the solar wind interaction with Jupiter's magnetosphere and aurora by using an MHD model of the propagated solar wind conditions to overcome the lack of upstream monitoring at the outer planets. The results will show whether there is evidence that the solar wind drives tail reconnection at Jupiter and Saturn, and will qualitatively and quantitatively describe how Jupiter's magnetosphere and aurora respond to changing solar wind conditions. We will specifically address whether the quasi-periodic behavior observed in Jupiter's magnetosphere may be controlled or modulated by the solar wind. We will also determine how Jupiter's main auroral emission responds to changing solar wind conditions, and compare our findings to theories and models. The results of the study will contribute generally to our knowledge of the fundamental physical processes involved in magnetic storms and in solar wind-magnetosphere coupling. It will provide an important step toward understanding the relative roles of the solar wind and internal factors in driving tail reconnection in giant planet magnetospheres. Comparative planetary studies such as the work proposed here are a useful, new approach for improving our understanding of the Sun-Earth connection.

6.*2 Broader impacts*

Boston University provides several education and public outreach activities that are an excellent match for my research interests and experiences. For example, BU's Department of Astronomy hosts a weekly public open night at their campus observatory in central Boston. I will become involved with this program, drawing on my experience as an undergraduate teaching assistant for an observational astronomy course at MIT. These public open nights are an excellent opportunity to interact with the public, since attendees will be able to see features like Jupiter's moons and Saturn's rings to pique their interest.

Additionally, I will engage with the student population at BU by serving as a mentor to both graduate and undergraduate students. Several of the research tasks described above, such as quantitatively examining periodic signals in the magnetospheric data sets, are at an appropriate level for an advanced undergraduate with programming skills. I will make an effort to recruit such an undergraduate to become involved with the proposed research. I will also volunteer for G-WISE (Graduate Women in Science and Engineering) at BU, by offering to host monthly coffee breaks to discuss themes such as developing collaborative networks, finding jobs post-graduation, and how to survive the peer review process.

In addition to the above activities, I will share the results of my proposed research through talks at scientific conferences and publications. I will also maintain and update an online web form, http://www.igpp.ucla.edu/people/mvogt/mapping, that was created to share the results of a Jovian magnetosphere/ionosphere mapping model [*Vogt et al.*, 2011]. This model has been used by members of the scientific community in interpreting auroral images from HST and in preparation for Juno's arrival in 2016 [e.g., *Bonfond et al.*, 2011; *Radioti et al.*, 2011].

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