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First Measurements of Jovian Electrons by Parker Solar Probe/IS⊙IS Within 0.5 AU of the Sun

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ABSTRACT

Energetic electrons of Jovian origin have been observed for decades throughout the heliosphere, as far as 11 astronomical units (au), and as close as 0.5 au, from the Sun. The treatment of Jupiter as a continuously emitting point source of energetic electrons has made Jovian electrons a valuable tool in the study of energetic electron transport within the heliosphere. We present observations of Jovian electrons measured by the EPI-Hi instrument in the Integrated Science Investigation of the Sun (IS⊙IS) instrument suite on Parker Solar Probe at distances within 0.5 au of the Sun. These are the closest measurements of Jovian electrons to the Sun, providing a new opportunity to study the propagation and transport of energetic electrons to the inner heliosphere. We also find periods of nominal connection between the spacecraft and Jupiter in which expected Jovian electron enhancements are absent. Several explanations for these absent events are explored, including stream interaction regions (SIRs) between Jupiter and Parker Solar Probe and the spacecraft lying on the opposite side of the heliospheric current sheet from Jupiter, both of which could impede the flow of the electrons. These observations provide an opportunity to gain a greater insight into electron transport through a previously unexplored region of the inner heliosphere.

1. INTRODUCTION

It has been recognized since the mid-1970's that Jupiter's magnetosphere is a persistent source of energetic (MeV) electrons in the heliosphere (Simpson et al. 1974; Teegarden et al. 1974; Chenette et al. 1974; Mewaldt et al. 1976). Indeed, these studies suggest that Jupiter is a dominant source of energetic (∼0.2-25 MeV) electrons in the heliosphere aside from solar energetic particle (SEP) events. A number of studies demonstrated that Jovian electron measurements from Earth-orbiting energetic particle instruments exhibit a 13-month periodicity, equal to the Jovian synodic period (e.g., Chenette et al. 1977). This led to the conclusion that this periodicity is due to the varying magnetic connection between the Earth and Jupiter along the interplanetary Parker spiral. These enhancements were generally observed over 4-8 month Jovian electron "seasons" with ∼27 day modulations due to the presence of co-rotating interaction regions[1] (CIR) between Jupiter and the observer (Chenette et al. 1977).

Electrons of Jovian origin have also been observed within the magnetospheres of other planets including the Earth (Baker et al. 1979) and Mercury (Baker 1986). This implies that electrons accelerated within the Jovian magnetosphere may seed these particles into the magnetospheres of other planets within the solar system, potentially contributing to the Earth's radiation belts (Baker et al. 1979) and becoming trapped within the Hermean system (Baker 1986). As a result, the contribution of Jovian electrons to other planetary systems

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[1] The more general term "stream interaction region" (SIR) will be used throughout this work to encompass both structures observed to co-rotate and those not observed to co-rotate.

is a rare example of a direct influence of one planet on another in our solar system.

The transport of Jovian electrons has been studied extensively at 1 astronomical unit (au), out to ∼11 au by Pioneer 10 and 11 (Pyle & Simpson 1977), and as close as 0.5 au to the Sun with Mariner 10 (Eraker & Simpson 1979). A number of studies have shown that Jovian electron propagation is modulated by the presence of SIRs in the interplanetary medium between the observing spacecraft and Jupiter (Conlon 1978). Conlon & Simpson (1977) demonstrated that SIRs located between Jupiter and the observer act as "impenetrable barriers" to the propagation of Jovian electrons (see also Strauss et al. (2016)).

Jovian electron energy spectra are typically observed to follow power law functions ($dJ/dE = CE^{-\gamma}$) with larger portions of high energy particles (termed "hard") and spectral indices in the range $\gamma = 1.4$ - 2 at energies $\lesssim$15 MeV (e.g., Eraker 1982; Moses 1987; Vogt et al. 2018; Mewaldt et al. 1976; Baker et al. 1979). This range of spectral index was consistent as close to the Sun as 0.5 au where Eraker & Simpson (1979) reported a spectral index of ∼1.4 ± 0.06 using Mariner 10 measurements.

In this letter, we present observations of Jovian electrons from the Parker Solar Probe (Fox et al. 2016) Integrated Science Investigation of the Sun (IS⊙IS) (McComas et al. 2016) high-energy Energetic Particle Instrument (EPI-Hi) (Wiedenbeck et al. 2017) as close as ∼0.28 au from the Sun. These are the closest observations of Jovian electrons to the Sun indicating that Jovian electrons propagate to very low heliocentric distances without being strongly impeded by the outward moving solar wind. We present the characteristics of these enhancements, highlighting similarities and differences compared with previously observed Jovian electron enhancements, as well as a discussion of times in which Jovian electron enhancements at Parker Solar Probe were expected, based on nominal connectivity to Jupiter, but not observed.

2. INSTRUMENTATION

EPI-Hi comprises three solid state detector (SSD) telescopes that measure energetic particles using a standard "dE/dx vs. total E" technique. Details of the EPI-Hi detectors are provided in McComas et al. (2016), Wiedenbeck et al. (2017) and Wiedenbeck et al. (2021). Electrons are distinguished from ions based on their location in dE/dx vs. residual energy space. EPI-Hi measures electrons in the energy range ∼0.5 - 6 MeV. As electrons readily scatter within the detector, conversion from instrumental count rate to incident flux is calculated using a response matrix technique utilizing Monte Carlo modeling of the instrumental response to electrons. These simulations were performed utilizing the Geant4 toolkit (Agostinelli et al. 2003) and will be the topic of a future publication.

EPI-Lo is a time-of-flight mass spectrometer that utilizes an SSD in each of its eight instrumental segments (wedges) to measure electrons (McComas et al. 2016; Hill et al. 2017; Mitchell et al. 2021). Each electron SSD has a thin ($\sim 3.2\mu m$) aluminum flashing to suppress low-energy ion signals. EPI-Lo measures electrons from ∼30 - 500 keV, such that the full energy range of electrons detectable by IS⊙IS is ∼30 keV to 6 MeV.

3. OBSERVATIONS

The observation of Jovian electrons by EPI-Hi was identified initially as a small (roughly factor of 2) but prolonged ∼5 day increase in the electron count rate without an accompanying enhancement in the ion count rates. Based on these features, small electron enhancements observed as the spacecraft exited Encounters ("Encounter" periods are defined as times during which the Parker Solar Probe spacecraft is within 0.25 au of the Sun) 7 and 9 in January and August 2021, respectively, were identified as candidate EPI-Hi Jovian electron observations. The enhancements are clearest at higher energies corresponding to particles stopping in deeper ranges of the EPI-Hi/High Energy Telescope (HET) SSD stack. These ranges have lower levels of background, allowing a clearer view of subtle features in the data. The ion data in both IS⊙IS instruments and the electron data in EPI-Lo showed no concurrent increase with the enhancement observed in the EPI-Hi electron channels, indicating that this enhancement was confined to higher energy electrons, as is commonly observed in Jovian electron measurements (Vogt et al. 2018). The January and August 2021 time periods, in which the Jovian enhancements began at the end of the Encounter periods, are the only observed instances of a prolonged enhancement in the electron count rate without enhancements in the ion channels during the first eleven Parker Solar Probe solar encounters.

A calculation of the connectivity between Parker Solar Probe and Jupiter along a nominal Parker Spiral, utilizing the HelioPy software (Stansby et al. 2019), revealed a likely magnetic connection between the spacecraft and Jupiter during both time periods identified above. An example of the connection between the spacecraft and Jupiter along a Parker spiral for 20 August 2021, the onset of the observed 2021 August Jovian electron enhancement, is shown in Fig. 1 using several solar wind speeds. Connectivity between the Parker Solar Probe spacecraft and Jupiter was calculated along a Parker

Spiral using a range of solar wind speeds from 360 to 410 km/s throughout the mission and times of expected connectivity were compiled. The chosen range of solar wind speeds was based on monthly averages from the Advanced Composition Explorer (ACE) Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) (McComas et al. 1998) bulk solar wind velocity measurements at 1 au. Parker Solar Probe Solar Wind Electrons Alphas and Protons (SWEAP) (Kasper et al. 2016) solar wind velocities were also examined and showed significantly greater variability due to the range of solar radii at which the solar wind was sampled. ACE SWEPAM data were used to represent the relatively stable ambient solar wind speed observed at more distant solar radii. Two thirds of the monthly average solar wind speeds from SWEPAM over the first 27 months of the Parker Solar Probe mission fell into the above range, indicating that these represented realistic typical conditions. A range of solar wind speeds, as opposed to a single average speed, was used to compensate for the fact that the speed used in this calculation is simply an estimate and will not be appropriate during all time periods. As well, it may be unrealistic to assume that the solar wind speed remains constant from the Sun to Jupiter's location at 5.2 au, though the average will likely be relatively constant (e.g. Collard et al. 1982). In addition to the uncertainty in the connection timing due to the variability in the solar wind speed, there is a contribution to the uncertainty from the effect of field line meandering (Jokipii & Parker 1969; Laitinen et al. 2013) that makes the precise time period of connectivity between Parker Solar Probe and Jupiter challenging to calculate. A sense of the uncertainty related to field line meandering can be provided by a calculation of the systematic deviation of the observed interplanetary magnetic field (IMF) winding angle from the Parker spiral expectation. Using the technique from Smith & Bieber (1991), ACE SWEPAM solar wind speeds and ACE Magnetic Field Experiment (MAG) (Smith et al. 1998) data for the times of nominal connectivity were used to calculate the observed IMF winding angle and expected winding angle during periods of nominal connectivity between Parker Solar Probe and Jupiter. From these calculations, we find a $\sim 22^\circ$ deviation of the observed IMF winding angle compared with the expected winding angle. While this provides an estimate for the uncertainty, a more precise estimate would require magnetic field and solar wind measurements just outside the Jovian magnetosphere. The Sub-Parker Spiral (Murphy et al. 2002; Schwadron 2002; Schwadron & McComas 2005; Schwadron et al. 2021) provides more radial connections through rarefaction regions, enabling more direct electron transport through the inner heliosphere which may add additional uncertainty to the connectivity time periods. The use of this range of solar wind speeds is intended to account for these uncertainties to calculate approximate time periods of connectivity.

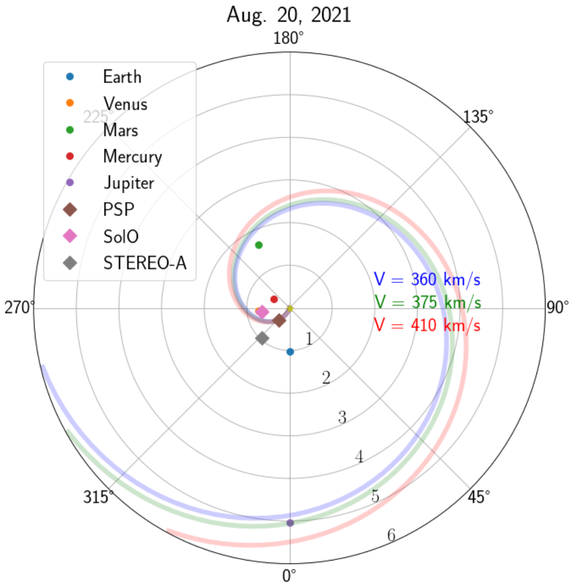

Figure 1. Connectivity diagram showing the connection along a nominal Parker Spiral using a range of solar wind speeds (blue - 360 km/s, green - 375 km/s, red - 410 km/s) between Parker Solar Probe and Jupiter for 2021 Aug. 20. Locations of Parker Solar Probe (PSP), Solar Orbiter (SolO) and the Solar Terrestrial Relations Observatory A (STEREO-A) are shown as diamonds. Numbers around the edge indicate Heliocentric Earth Equatorial (HEEQ) longitude.

The heliocentric distance of Parker Solar Probe as a function of time for the entire mission to date is shown in Fig. 2. The vertical red boxes in that figure show the time periods of nominal connectivity between the spacecraft and Jupiter using the technique described above, where the width of the boxes represent the result of using the range of solar wind speeds. As evidenced by Fig. 2, we presently expect Parker Solar Probe to be connected to Jupiter each time the spacecraft comes out of Encounter, providing the possibility of Jovian electron observations by IS⊙IS in each spacecraft orbit.

Early in the Parker Solar Probe mission (i.e. prior to 2021), this calculation yielded a connection time between the spacecraft and Jupiter of 6-7 days on average. During 2021, however, the calculated connection time between the spacecraft and Jupiter grew to 8-10 days on average due to the changing orbital parameters as the mission progresses (this is reflected by the increasing width of the red boxes in Fig. 2). In contrast, the same calculation performed at Earth results in nominal connection times of ∼54 days on average.

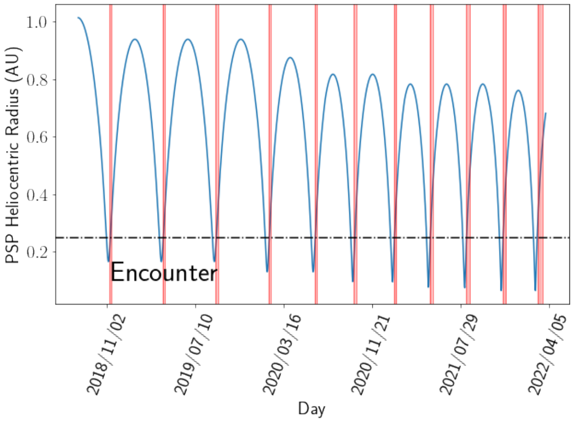

Figure 2. Parker Solar Probe heliocentric distance as a function of time. Vertical red boxes denote time periods in which the spacecraft is expected to be magnetically connected to Jupiter along a nominal Parker Spiral using a solar wind speed range of 360-410 km/s (width of the boxes is due to the range of solar wind speeds used in the calculation). Times when the spacecraft is less than 0.25 au from the Sun (shown as the horizontal black line) are solar encounter periods.

The EPI-Hi/HET ∼0.9 - 5.7 MeV electron count rate, with solar energetic particle (SEP) events removed, was examined for the entire mission. SEP events were identified as times in which daily averages of the EPI-Hi/HET proton count rates in the energy range ∼6.7-19 MeV were elevated above typical statistical fluctuations (2σ above the mean quiet time count rate produced a threshold of $\sim 1 \times 10^{-3}$ counts/sec). A more conservative measure of 0.9 counts/sec average was used to ensure removal of SEP enhancements. Days prior to SEP enhancements were also removed to account for the early arrival of electrons compared with ions. Fig. 3 shows daily averages of the EPI-Hi/HET electron count rate time series throughout the year 2021 in the energy range 0.9-5.7 MeV. The vertical red boxes mark time periods of nominal connectivity of Parker Solar Probe to Jupiter. The horizontal blue dashed line shows the average count rate over this time period. The first (∼DOY 25) and third (∼DOY 230) time periods in which the spacecraft is expected to be connected to Jupiter have clear enhancements above background near the time of expected connectivity based on the range of solar wind speeds used. A Gaussian fit of the 2021 HET electron count rate daily averages was used to estimate the significance of the enhancements in the January and August time periods. The clearest enhancement in August (∼DOY 230) is characterized by three daily averages in a row with greater than 6σ enhancements above the mean of the fit. The January time period (∼DOY 25) with a smaller enhancement had three days in a row with a greater than 3σ enhancement above the mean. The rarity of this significance level of enhancement, in conjunction with the fact that these enhancements took place on consecutive days clearly demonstrates that while these enhancements are smaller than typical SEP electron events, they are unlikely to be random statistical fluctuations. The second and fourth periods of expected connectivity near DOY 125 and DOY 330, respectively, appear to have small enhancements above background that may be due to Jovian electrons. However, as they are not as clear as those on DOY 25 and 230, we focus our attention on the larger enhancements.

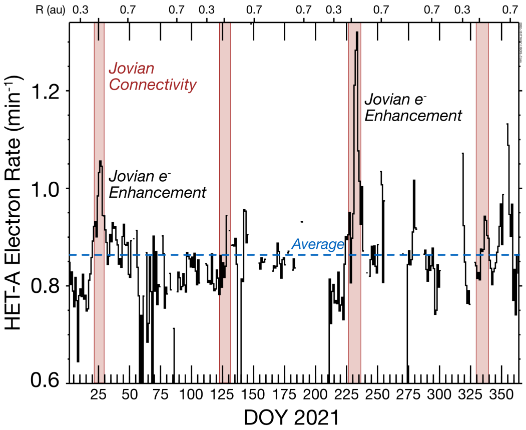

Figure 3. EPI-Hi/HET daily averaged 0.9 - 5.7 MeV electron time series throughout 2021. Times of nominal connectivity between Parker Solar Probe and Jupiter are marked by the vertical red boxes. Horizontal blue dashed line denotes the mean count rate during this time period.

Fig. 4 shows daily averages of the high energy electron time series over the entire mission to the time of writing. Vertical red boxes again denote time periods in which the spacecraft is expected to be connected to Jupiter while vertical blue boxes mark days in which SIRs were identified in the Parker Solar Probe SIR/CIR list[2] (Allen et al. 2020). The data gap during the end of 2019 into the beginning of 2020 was a time period in which EPI-Hi was not taking measurements in order to investigate an instrumental anomaly. The abrupt discontinuity in count rate approximately halfway through 2019 is due to an instrument commanding that modified the criteria used to identify electron signals. There

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[2] https://sppgway.jhuapl.edu/Event_Lists/SIR_CIR_List_PSP.csv

are no obvious Jovian electron events identified in the EPI-Hi data other than those mentioned above in 2021 January and August. The first period of connectivity in 2022 may contain a Jovian electron enhancement, however, it occurs between two SEP events, thus limiting the ability to carefully study this possible enhancement.

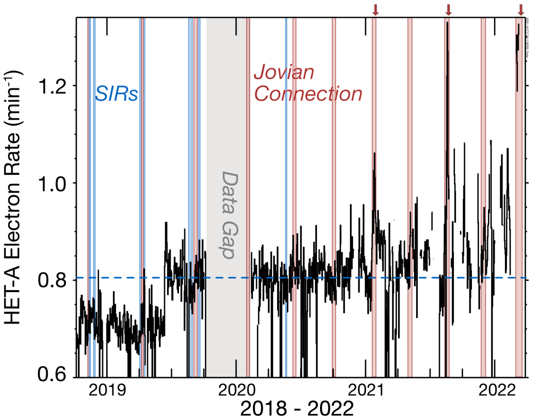

Figure 4. EPI-Hi HET daily averaged 0.9 - 5.7 MeV electron count rates throughout the entire mission to the time of writing. Vertical red boxes indicate periods of nominal connectivity between Parker Solar Probe and Jupiter. Blue vertical boxes indicate times in which IS⊙IS observed SIRs.

Energy spectra were generated for the time periods in which Jovian electrons were observed and a pre-event background was subtracted to isolate the spectrum of the Jovian electrons. As it has the largest enhancement above background, the spectrum for the 2021 August time period is used to infer the spectral characteristics of Jovian electron measurements by EPI-Hi at these solar radii (Fig. 5). Both HET-A and HET-B exhibit power-law spectra with spectral indices of ∼2.0 in the HET energy range with the most reliable response. Energy bins at the borders of instrumental response are omitted due to known instabilities in the response matrix technique at these energies.

4. DISCUSSION

Previous observations of Jovian electrons at 1 au show increases in the electron rates that can last for months at a time and recur on a 13 month basis, in agreement with Jupiter's synodic period and connectivity with the Earth. The observed IS⊙IS Jovian electron enhancements are much briefer (less than 1 week in duration) than those observed by other instruments. These differences are supported by the much greater orbital velocity of Parker Solar Probe than the Earth and are exemplified by the above calculation in which the nominal connection time of Parker Solar Probe was less than 10 days compared with 54 days at Earth. Coming out of encounter at 0.25 au, the Parker Solar Probe spacecraft has a velocity of approximately ∼60 km/s (roughly double the Earth's speed in its orbit) and changes heliolongitude much more quickly than the Earth (∼2-5 degrees per day compared with ∼1 degree per day at Earth), hence the much briefer period of magnetic connection between Parker Solar Probe and Jupiter. Parker Solar Probe's highly elliptical orbit shape (eccentricity ∼0.88) likely also plays a key role in the brevity of these Jovian electron enhancements compared with the Earth (eccentricity 0.0167).

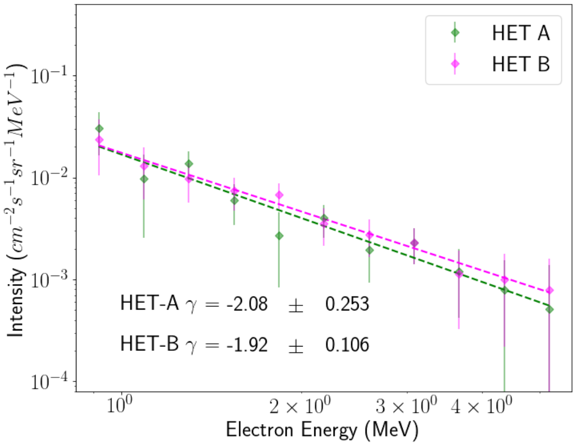

Figure 5. Background-subtracted average differential intensity spectrum measured by IS⊙IS/EPI-Hi/HET during the most pronounced Jovian electron enhancement observed to date (2021 August 19 - 22 inclusive). "HET-A" and "HET-B" indicate the two ends of the double-ended HET telescope. Spectrum is fit in the energy range ∼0.9-5.2 MeV.

As shown in Fig. 4, EPI-Hi did not observe a clear Jovian electron enhancement until the beginning of 2021 despite five earlier time periods in which Parker Solar Probe was nominally magnetically connected to Jupiter and EPI-Hi was operating. This lack of clear Jovian electron enhancements during earlier periods of connectivity may be due to the presence of SIRs in the interplanetary medium between the spacecraft and Jupiter. Fig. 4 shows that SIRs were observed by IS⊙IS prior to most time periods in which we would expect to observe a Jovian electron enhancement. Due to the brief interval of expected connectivity, an SIR between the spacecraft and Jupiter can result in an absent Jovian electron enhancement, as opposed to the typical interrupted Jovian electron enhancements observed by Earth-based spacecraft which remain connected to Jupiter for a far longer time interval (Chenette 1980).

While the correlation between the absent Jovian electron enhancements and the SIR-associated enhancements observed by IS⊙IS prior to connectivity between the spacecraft and Jupiter appears a likely contributor to the absence of these enhancements, previous studies of periods in which expected Jovian electron enhancements were absent from other instruments have postulated that the cause is in fact modulation of the Jovian electron source (Kanekal et al. 2003; Morioka & Tsuchiya 1996).

In addition to the postulated causes for the absence of expected Jovian electron enhancements observed by IS⊙IS, we have also investigated the possibility that the Parker Solar Probe spacecraft and Jupiter lying on opposite sides of the heliospheric current sheet (HCS) may play a role in the modulation of Jovian electrons. The HCS may serve as an obstacle to electron transport such that an observer located on the opposite side of the HCS from Jupiter may not observe a Jovian electron enhancement even when otherwise in a region of nominal connectivity (e.g. Smith 1990; Battarbee et al. 2017; Pezzi et al. 2021). Fig. 6 shows a time series of the EPI-Hi/HET-A electron count rate in the top panel and the radial component of the magnetic field as measured by the Parker Solar Probe Electromagnetic Fields Investigation (FIELDS) magnetometers (Bale et al. 2016) in the bottom panel (Fränz & Harper 2002). The Jovian electron enhancement observed by HET-A is bookended by the spacecraft crossing the HCS and entering a positive IMF polarity on DOY 229 and crossing back into a negative IMF polarity on DOY 234 (indicated by grey shaded regions in both panels). WSA-ENLIL modeling (Odstrcil et al. 2020) performed by the NASA Community Coordinated Modeling Center (CCMC) indicates that during this time period, Jupiter was likely in a positive IMF polarity, in agreement with the notion that Jovian electrons are unable to reach Parker Solar Probe when the spacecraft is on the opposite side of the HCS from Jupiter. Investigation of several other time periods indicate that this may be at least a contributing factor when IS⊙IS does not observe Jovian electron enhancements. The brevity of the connection times between Parker Solar Probe and Jupiter may also contribute to effects from the HCS. If the magnetic connection is long compared with a solar rotation (as it is at Earth), both Jupiter and the observer would likely sample both sides of the HCS during a given connection time period such that both bodies would likely lie on the same side of the HCS for at least a portion of the time period of connection. However, if the connection duration is short compared with a solar rotation, it is possible that only one side of the HCS is sampled by the observer, which may or may not be on the same side as Jupiter. Further study is required to fully understand whether these absent events are due to impediment from SIRs or the HCS, modulation of the source, short connection time periods, or perhaps a separate mechanism (e.g. the sub-Parker spiral) due to Parker Solar Probe's close proximity to the Sun at the time of connectivity.

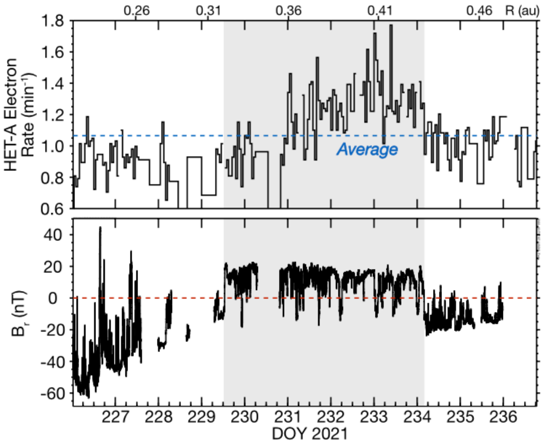

Figure 6. Example that may indicate that Jovian electrons are modulated by the HCS. The top panel shows IS⊙IS/EPI-Hi/HET-A electron count rates during the time period around the observed 2021 August Jovian electron enhancement. The bottom panel shows the radial component of the magnetic field measured by FIELDS. Jovian electrons are not observed prior to DOY 229 when Parker Solar Probe crosses the HCS, going from a region of negative IMF polarity to positive IMF polarity (grey shaded region). The Jovian electron enhancement ends at the time when the spacecraft crosses the HCS to re-enter a negative IMF polarity region.

During the 2021 August Jovian electron enhancement observed by EPI-Hi, the HET-A and HET-B average intensity spectra were fit well with a spectral index of 2.08 ± 0.253 and 1.92 ± 0.106, respectively, after background subtraction to isolate the Jovian electron component. This spectral index is comparable to previously reported spectral indices at 1 au of the Sun. That said, Eraker & Simpson (1979) reported a very hard spectrum with a spectral index of 1.41 ± 0.06 at 0.5 au for a 16 day time period in 1974 in which Mariner 10 observed a Jovian electron enhancement. This is the measurement with the most comparable solar distance to the observations in the present work. A physical interpretation of this difference could be that higher energy Jovian electrons do not propagate in as far to the Sun, producing a relatively steeper observed spectrum. This goes against intuition of electron transport processes, as one would generally expect to observe harder spectra as the observer approaches the Sun due to increased scattering of lower-energy electrons and adiabatic energy changes. Future measurements of Jovian electrons by IS⊙IS are required to begin truly characterizing the Jovian electron spectrum at these solar distances and determine if this softer spectrum is a systematic feature of the transport of Jovian electrons closer than previously measured or simply an individual anomaly of this particular time period.

5. SUMMARY AND CONCLUSION

In this work, we identified periods of prolonged quiet time increases in the IS⊙IS/EPI-Hi electron count rates and argued that these enhancements are likely the first observations of Jovian electrons as close as 0.28 au from the Sun. We noted that the duration of the enhancements observed by EPI-Hi are much briefer than those studied by Earth-orbiting spacecraft due to the high speed and orbital eccentricity of Parker Solar Probe. We also discussed the absence of a clear Jovian electron enhancement observed by EPI-Hi during several of the periods of nominal magnetic connection and postulated that this may be due to modulation of the Jovian electrons by SIRs located between the spacecraft and Jupiter. Other potential causes for these absent events include a change in the Jovian electron source, modulation by the presence of the HCS between Parker Solar Probe and Jupiter, brevity of magnetic connectivity between the spacecraft and Jupiter, or an as yet unidentified effect from Parker Solar Probe's close proximity to the Sun during times of connectivity. The evidence that Jovian electrons may be modulated by the HCS is a unique observation which may indicate a greater importance of the HCS in the modulation of energetic particles near the Sun than observed at 1 AU (Pezzi et al. 2021). It is also possible that multiple effects contribute to these absent Jovian electron events. We examined the Jovian electron spectrum during the largest enhancement observed and find that it is in the range of previously reported spectral indices from other instruments (1.4 - 2), though on the soft end of that range.

These observations are noteworthy as they mark the closest observation of electrons of Jovian origin to the Sun, indicating that this population can propagate into these low solar distances without being inhibited by the outward moving solar wind. These observations are also significant in their temporal, and possibly spectral, differences compared with previous observations of Jovian electrons. Observations of Jovian electrons at these solar distances provide novel opportunites to study the influence of solar proximity and magnetic connection to the Jovian source for energetic-particle transport models (e.g. Strauss et al. 2011).

The Jovian electron observations presented in this work also provide valuable information to aid in the study of particle transport mechanisms. In particular, Jovian electrons are often utilized as test particles by the energetic particle transport modeling community to estimate parallel and perpendicular diffusion coefficients and compare these estimates with theoretical predictions. Despite decades of study, models often arrive at highly variable values for diffusion coefficients (e.g. Engelbrecht et al. 2022). IS⊙IS observations of Jovian electrons from the inner heliosphere will constrain model-based estimates of energetic electron diffusion coefficients and yield additional insights to electron transport in this previously unexplored region.

The present observations also leave us with outstanding questions. While a transport barrier from SIRs in the interplanetary medium seems a likely explanation for the lack of observations of Jovian electrons earlier in the mission due to the large number of SIRs observed and the well-established modulation of Jovian electrons by SIRs, it is possible that there are other factors that should be considered, several of which have been postulated above. It remains to be seen whether the softness of the observed spectrum compared with other measurements (particularly those at 0.5 au) is a statistical artifact or a clue to the transport physics at play as Jovian electrons propagate into the inner heliosphere. Future comparisons of Jovian electron enhancements at Parker Solar Probe, Solar Orbiter, and 1 au spacecraft will allow the temporal, longitudinal, and radial examination of these enhancements. Fortunately, the nominal magnetic connectivity of Parker Solar Probe to Jupiter with each orbit means there will likely be many opportunities to shed light on these questions in future orbits.

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