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REAPPRAISAL OF THE *PIONEER 10* AND *VOYAGER 2* Lyα INTENSITY MEASUREMENTS

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ABSTRACT

The *Pioneer 10* (*P10*) and *Voyager 2* (*V2*) calibration difference of 4.4 at Lyα has made it difficult to interpret the Lyα data and also to resolve the outer planetary upper atmosphere excess Lyα glow problem. We have carried out radiative transfer calculations using an improved radiative transfer code and six heliosphere neutral-plasma density models to study the calibration of *P10* and *V2* at Lyα and found that both *P10* and *V2* intensity measurements are in need of revision. The intercalibration difference is discussed using our model calculations, recent large-distance neutral hydrogen density determinations obtained from pickup-ion and solar wind slow-down data, the recent change in the estimate of the solar Lyα flux values, and *Voyager 1* energetic particle measurements. These recent heliospheric measurements and Lyα glow model calculations support the need for an upward revision of *P10* and a downward revision of *V2* Lyα intensity. It is not yet possible to give a definitive estimate of the required revision because of lack of knowledge of the very local interstellar medium neutral hydrogen density. The calibration revision is found to reduce the range of variation of Jovian dayglow.

Subject headings: interplanetary medium — ISM: atoms — solar wind

1. INTRODUCTION

Remote sensing of the heliosphere, the complicated circumsolar region shaped by the interaction of the solar wind with the plasma and neutral components of the very local interstellar medium (VLISM), has been made possible by the presence of four deep space spacecraft, *Pioneer 10* and *11* (*P10*/*11*) and *Voyager 1* and *2* (*V1*/*2*). These spacecraft have also made a detailed study of the outer planets (Jupiter, Saturn, Uranus, and Neptune) possible. The *P10*/*11* photometric and the *V1*/*2* spectrometric observations of Lyα glow backscattered from the VLISM neutral hydrogen atoms flowing into the solar system have been used to determine the neutral hydrogen density in the heliosphere. These number density estimates obtained from glow measurements are, however, crucially dependent on the absolute calibration of the *P10*/*11* photometers and *V1*/*2* spectrometers. Hence, any uncertainty in the absolute calibration of the different instruments would lead to errors in the estimation of the neutral density.

It has, in fact, been known for about two decades that *P10* photometer and *V2* spectrometer calibrations differ by a factor of 4.4 at Lyα (Shemansky et al. 1984; Shemansky & Judge 1988). This difference was computed by comparing the backscattered Lyα glow measured by the two instruments at Lyα wavelength on day 278, 1979. This calibration difference has made it very difficult to realize the full potential of the combined data sets, for both the heliosphere and the outer planetary upper atmospheres. This is extremely unfortunate as *V1*/*2* and *P10* are sampling the upstream and downstream regions (with respect to the incoming neutral hydrogen flow) of the heliosphere, respectively, and the well-calibrated combined data sets would be uniquely helpful in the study of the VLISM. A recalibration of the *P10* photometer and the *V1*/*2* spectrometers would also be very useful for upper atmosphere Jovian studies. The measurements of Jovian dayside Lyα glow during the early part of the 1970 decade (Rottman et al. 1973; Carlson & Judge 1974; Giles et al. 1976) indicate an apparent variable disk averaged brightness (Shemansky & Judge 1988) with the *P10* observation in late 1973 being the all-time low in the history of Jovian EUV observations (Table 1). Since 1973 Jovian dayside glow has been measured (Table 1) by *Voyager* (Shemansky 1985), *Cassini* (Shemansky et al. 2003), the Hopkins Ultraviolet Telescope (HUT; Feldman et al. 1993), *International Ultraviolet Explorer* (*IUE*; Skinner et al. 1988), a sounding rocket (Clarke et al. 1980), and *Galileo* (Gladstone et al. 2004). All these post-1973 reported observations obtained higher brightnesses of between 7000 and 15,000 R, which far exceed the approximately 5000 R expected from the resonance scattering of the solar Lyα line during solar maximum (Gladstone 1988; Shemansky et al. 2003). The *V2* measurement of a 15,000 R Jovian Lyα glow during solar maximum is a factor of 3 greater than the expected solar Lyα resonance contribution. The additional energy for the excitation process powering the post-1973 Jovian dayglow cannot be obtained from photoionization, although the emission must be stimulated by solar input (Broadfoot et al. 1979; Sandel et al. 1982; Shemansky 1985; Shemansky & Smith 1986; Shemansky & Judge 1988). The Jovian glow is powered by a uniformly distributed particle excitation on the dayside of the planet that is apparently disconnected from the auroral activity (Shemansky 1985; Shemansky & Smith 1986; Shemansky & Judge 1988). Of course, the exact amount of additional energy needed to power the Jovian glow is critically dependent on our knowledge of the calibration of the various instruments on board the space craft. A correction for known discrepancies in the calibration of the various instruments is necessary for the understanding of the morphology of the Jovian dayglow over the three-decade period.

Our approach to the solution of the intercalibration problem is to compare *P10* and *V2* data with the heliospheric backscattered solar Lyα glow for VLISM plasma-neutral models using different neutral hydrogen and proton densities. State-of-the-art heliospheric plasma-neutral models incorporating the interaction between the solar wind and the VLISM and radiative transfer code are employed to carry out this comparison. The

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TABLE 1
Sets of Jovian Dayglow Measurements

Spacecraft	Year of Observation	Lyα Intensity (R)	H2, Lyman, and Werner Band Intensities (R)	F10.7 (10^{-22} W m^{-2} s^{-1})
Sounding rocket (Rottman et al. 1973)	1971	4400	9700	170
Sounding rocket (Giles et al. 1976)	1972	2200	5800	100
P10 (Carlson & Judge 1974)	1973	Total of 400		70
Sounding rocket (Clarke et al. 1980)	1978	13000	...	160
Voyager (Shemansky et al. 1985)	1979	15000	2900	170
IUE (Skinner et al. 1988)	1978–1986	13000–7000	...	160–63
HUT (Feldman et al. 1993)	1990	15100	2265	180
Galileo (Gladstone et al. 2004)	1997	15000	...	85
Cassini (Shemansky et al. 2003)	1999	11700	2300	160

methodology of our calculation is briefly discussed in the next section. The data, the results, and the conclusion are discussed in the subsequent sections.

2. METHODOLOGY

A study of the heliospheric Lyα glow requires a VLISM hydrogen model and a radiative transfer code. The VLISM neutral hydrogen density distribution is very difficult to calculate since the interaction of the solar wind with the inflowing interstellar medium influences the distribution of interstellar atoms inside the heliosphere. Further, it is now clear that the Local Interstellar Cloud (LIC) is partly ionized and that the plasma component of the LIC interacts with the solar wind plasma to form the heliospheric interface. Interstellar H atoms interact with the plasma component, strongly influencing both the plasma and neutral components. The main difficulty in modeling the H atom flow through the heliospheric interface is its kinetic character, which is due to the large, i.e., comparable to the size of the interface, mean free path of H atoms with respect to the mean free path for charge exchange. In this paper we get the H atom distribution in the heliosphere and heliospheric interface structure by using the self-consistent model developed by Baranov & Malama (1993). The kinetic equation for the neutral component and the hydrodynamic Euler equations were solved self-consistently by the method of global interactions. To solve the kinetic equation for H atoms, an advanced Monte Carlo method with splitting of trajectories (Malama 1991) was used. Basic results and recent advancements of the model were reported by Baranov & Malama (1995), Izmodenov et al. (1999b, 2001), and Izmodenov (2000, 2003, 2004).

The Monte Carlo radiative transfer calculation performed here is a revised version of the code published in Gangopadhyay et al. (1989). As a check on the validity of the code, we note that the original 1989 code agreed with Keller et al. (1981) for a hot hydrogen model, as expected. The 1989 code included a flat solar line, multiple scattering, complete frequency redistribution, constant hydrogen temperature, and Doppler absorption profile. The 1989 model has since been revised to incorporate the actual self-reversed solar line shape, full angular and frequency redistribution function, Doppler and aberration effects, heliosphere-wide hydrogen temperature and velocity changes, and Voigt Lyα absorption profile. The model is discussed in detail in Gangopadhyay et al. (2002).

3. DATA

We have used *P10* daily averaged Lyα data obtained in the downwind direction with respect to the incoming interstellar flow at large heliocentric distances, i.e., between 20 and 45 AU, in the present work. The *P10* data were obtained between 1979 and 1988. The detector look angle traces out a conical shell (apex angle = 40° and shell thickness = 1°) about the spacecraft spin axis, which is pointed approximately toward the Earth. The *P10* look directions for all the data points used here pointed away from the Galactic center, making an angle of approximately 160° with it. The details of the *P10* instrument are given in Carlson & Judge (1974).

We used *V2* daily averaged Lyα data at large heliocentric distances between 39 and 55 AU. The data were obtained between 1993 and 1998, when the spacecraft was in the upwind direction with respect to the incoming flow. The *V2* look directions for all the data points are nearly collinear with the position vectors and made an angle of approximately 20° with respect to the Galactic center. The UVS instrument is described in detail by Broadfoot et al. (1977, 1981).

The time and position of the *P10* and *V2* data used here are given in Table 2.[4] The solar Lyα intensities given in the table are mostly actual measurements, although SME measurements have been rescaled to match the SUSIM UARS calibration and the He 10830 Å has been used as a proxy to fill in some gaps. The solar line shape was assumed to be fixed for all the data points, although there is a possibility that the line shape might change during the solar cycle (Lemaire et al. 1998).

4. RESULTS AND DISCUSSION

Monte Carlo radiative transfer calculations (Gangopadhyay et al. 2002, 2004; Izmodenov et al. 2003) were carried out for six neutral hydrogen density models. The calculated results for the neutral-density models were then compared with *P10* (Gangopadhyay et al. 2002) and *V2* EUV data. The *P10* and *V2* data and calculations for a particular density model are shown in Figure 1 and are also given in Table 3. All six models show differences like that seen between observations and calculations in Figure 1. It is clear from Figure 1 and Table 3 that it is necessary to revise the *P10* and *V2* intensity rayleigh values by calibration factors (CFs) in order to fit the model calculations with the observations. The optimum calibration factor for a density model is calculated by minimizing the least-squares sum (LSS), where LSS is calculated using the following equation:

$$\mathrm{LSS} = \sum [1 - (\mathrm{bg} - \mathrm{CF} \times I_{P10\ \mathrm{or}\ V2\ \mathrm{data}})/I_{\mathrm{model}}]^2, \qquad (1)$$

where the summation is over the *P10* or *V2* data points, I_{model} is the calculated backscattered intensity, $I_{P10\ \mathrm{or}\ V2\ \mathrm{data}}$ is the

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[4] The solar Lyα flux values were obtained from the http://spacewx.com (see Woods et al. 2000).

TABLE 2
Spacecraft Data Sets

Spacecraft	Year	Day	Heliocentric Distance (AU)	Sun-centered Ecliptic Latitude (deg)	Sun-centered Ecliptic Longitude (deg)	Solar Lyα Flux (10^{11} × photons cm^{-2} s^{-1})
P10	1979	298	20.0043	3.1	58.3	5.70
	1980	252	22.5058	3.1	61.0	5.40
	1981	207	25.0001	3.1	63.0	5.19
	1982	167	27.5037	3.1	64.8	5.05
	1983	129	30.0002	3.1	66.2	5.10
	1984	95	32.5061	3.1	67.5	4.71
	1985	61	35.0067	3.1	68.5	3.89
	1986	30	37.5069	3.1	69.0	3.52
	1987	1	40.0006	3.1	70.0	3.72
	1987	338	42.5012	3.1	71.0	4.01
	1988	314	45.0111	3.1	71.7	5.03
V2	1993	64	39.5	−12.2	283.3	4.88
	1993	147	40.2	−12.8	283.5	4.52
	1993	183	40.4	−13.1	283.5	4.38
	1993	294	41.3	−13.8	283.7	4.06
	1994	172	43.2	−15.5	284	3.75
	1994	275	44	−16.1	284.2	3.74
	1995	87	45.4	−17.2	284.4	3.83
	1995	230	46.6	−18	284.6	3.72
	1995	328	47.4	−18.5	284.7	3.72
	1996	96	48.5	−19.2	284.9	3.62
	1996	183	49.2	−19.7	284.9	3.71
	1996	338	50.4	−20.4	285.1	3.56
	1997	37	51	−20.7	285.2	3.66
	1997	99	51.5	−21	285.3	3.74
	1997	161	52	−21.3	285.3	3.54
	1997	203	52.3	−21.5	285.4	3.60
	1997	278	53	−21.8	285.4	3.82
	1997	328	53.4	−22	285.5	4.04
	1998	46	54.1	−22.3	285.6	4.01
	1998	126	54.7	−22.7	285.6	4.23
	1998	171	55.1	−22.8	285.7	4.15

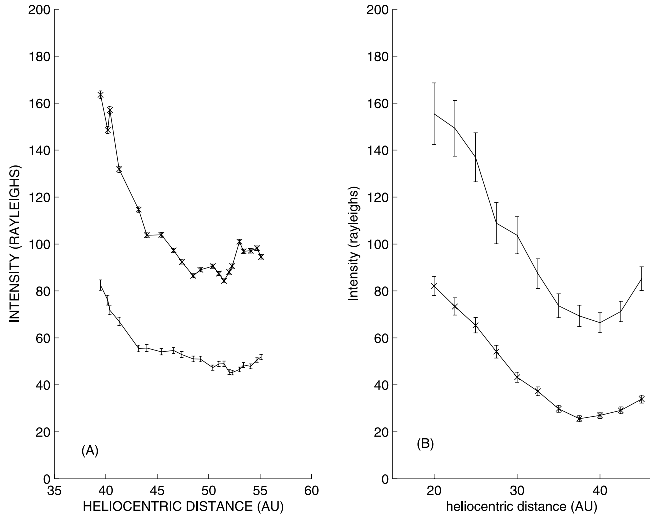

Fig. 1.—(*a*) Comparison of Monte Carlo calculated intensities using a heliospheric model (neutral hydrogen density of 0.15 cm^{-3} and proton density of 0.05 cm^{-3}; *lower line with error bars*) with *V2* data (*crosses*). The uncertainty associated with the *V2* data is on the order of 1%. (*b*) Comparison of Monte Carlo calculated intensities (*upper line with error bars*) with *P10* data (*crosses*). The uncertainty associated with the *P10* data are on the order of 5%.

spacecraft intensity value, and bg is the Lyα Galactic background. We have used a background peaked about the Galactic center. The expression used for the background was bg $= a\exp(-\alpha_{\rm diff}/5.0)$, where $\alpha_{\rm diff}$ is the angle between the look direction and the Galactic center. Both CF and bg were varied to obtain the minimum LSS. Once the optimum CF and bg are found, then *P10* or *V2* data are multiplied by CF and compared with the calculated intensity. Both CF and LSS are given in the Tables 4 and 5. We found that a zero Galactic background best fit the data for all the density models used. Shemansky et al. (1984), Gangopadhyay et al. (2002), and Quemerais et al. (2003) have also found a low Galactic Lyα background.

What is startling about the results obtained here is that both the *P10* and the *V2* intensity R values fall well outside the range of intensities calculated for the six heliospheric models. The implication is that the VLISM neutral hydrogen density is less than 0.1 cm^{-3} for the *P10* calibration while the VLISM neutral hydrogen density is greater than 0.25 cm^{-3} for the *V2* calibration. The low 0.12 cm^{-3} obtained for VLISM neutral hydrogen density by Shemansky et al. (1984) from *P10* and *V2* glow data is due to the fact that they did not take into account the filtration due to any shock structure. The Shemansky et al. (1984) value is more or less appropriate for the value inside the termination shock and needs to be adjusted upward to indicate the implied VLISM value before filtration in the proposed shock structures. In addition, the solar Lyα flux value used by Shemansky et al. (1984) has since been revised upward (Woods & Rottman 1997;

TABLE 3

Comparison of Observed and Calculated Lyα Intensity

Heliocentric Distance (AU)	Lyα Intensity Observed (R)	Lyα Intensity Calculated (R)
P10		
20.0043	82.1	152.1
22.5058	73.4	146.9
25.0001	65.4	133.3
27.5037	54.1	116.6
30.0002	43.2	107.9
32.5061	37.3	91.7
35.0067	29.8	75.9
37.5069	25.6	71
40.0006	27.0	69.3
42.5012	29.2	71.4
45.0111	33.9	82.5
V2		
39.5	163.5	82.5
40.2	148.6	76.1
40.4	157.1	71.8
41.3	131.8	67
43.2	114.7	55.5
44	103.7	55.7
45.4	103.9	54.1
46.6	97.3	54.6
47.4	92.4	52.9
48.5	86.5	51
49.2	89	51
50.4	90.6	47.3
51.0	87.4	48.9
51.5	84.3	49
52	88	45.4
52.3	90.6	45.2
53	100.9	46.6
53.4	96.9	48.5
54.1	97.1	47.9
54.7	98.2	50.7
55.1	94.5	51.8

Note.—Hydrogen density is 0.15 cm^{-3} and photon density is 0.05 cm^{-3} in all cases.

Tobiska et al. 1997; Woods et al. 2000). The determination of the neutral hydrogen density of the order of 0.1 cm^{-3} at large heliocentric distances (possibly near the termination shock) by Gloeckler & Geiss (2001) and by Wang & Richardson (2001), with the implication of a VLISM neutral hydrogen density significantly higher than 0.1 cm^{-3}, would seem to call into question the *P10* calibration at Lyα since it is clear from Table 3 that *P10* calibration needs an upward revision by a factor of 2 for a neutral hydrogen density of 0.15 cm^{-3} and when the revised solar Lyα flux values are used. There may be no need for revising the *P10* calibration if the old solar Lyα flux values are used. There is thus observational evidence that the *P10* Lyα glow intensity needs to be revised upward at least for the type of heliospheric models shown here and for the revised solar Lyα flux values.

TABLE 4

Sets of Model Parameters and Results for *V2*

Neutral Hydrogen Density (cm^{-3})	Proton Density (cm^{-3})	$\sqrt{\mathrm{LSS}}$	CF	bg (R)
0.15	0.05	0.325	0.52	0
0.15	0.07	0.315	0.5	0
0.20	0.05	0.295	0.66	0
0.20	0.10	0.357	0.63	0
0.20	0.20	0.344	0.58	0
0.25	0.10	0.328	0.76	0

It is obvious that the *V2* calibration needs to be revised downward if the VLISM neutral hydrogen density is less than or equal to 0.25 cm^{-3} and if the revised solar Lyα values are used. There is currently no in situ direct observational data, and only various model-dependent estimates of the VLISM neutral hydrogen density are available. Gloeckler & Geiss (2001), for example, estimated from their pickup-ion measurement inside the termination shock a VLISM neutral hydrogen density of 0.18 cm^{-3}, assuming a 58% filtration effect. For such VLISM densities the *V2* calibration at Lyα needs to be revised downward and the *P10* calibration upward. Unfortunately, neither the amount of filtration nor the VLISM neutral density is currently well known, and it is not yet possible to determine the factors by which the *V2* and *P10* calibrations need to be revised. An additional point in favor of a downward revision of *V2* calibration is the fact that recent *V1* energetic particle measurements (Krimigis et al. 2003; McDonald et al. 2003) have detected evidence for a solar wind termination shock. Krimigis et al. (2003) have concluded from a large increase in anomalous cosmic rays and interstellar pickup ions that *V1* exited the supersonic solar wind on about 2002 August 1 at a distance of about 85 AU. McDonald et al. (2003) also found a simultaneous increase in Galactic cosmic-ray ions and electrons, anomalous cosmic rays, and low-energy ions; but they concluded from the low-intensity level and spectral energy distribution of the anomalous cosmic rays that *V1* has still not reached the termination shock but rather the observed increase is a precursor event. A termination shock at a heliocentric distance of 85 AU would imply that the VLISM neutral density is lower than 0.25 cm^{-3} (Izmodenov et al. 1999a), thus ruling out *V2* calibration. The termination shock crossing or observation of precursor event at 85 AU thus provides an additional constraint on the *V2* calibration. An exact estimate of the VLISM neutral hydrogen density from the recent *V1* energetic particle measurements is not currently available. A further point to note is that the *V2* observation of the flux of the white dwarf star HZ 43 was found to be an overestimate (Holberg et al. 1982) by a factor of 1.6. It must be pointed out, however, that stellar calibrations do not specifically address the calibration question at Lyα.

It must be emphasized here that the huge discrepancy between the calculated intensities and *P10* and *V2* observations for all six heliosphere models cannot be due to heliosphere models not incorporating the correct filtration factor. The fact that the

TABLE 5

Sets of Model Parameters and Results for *P10*

Neutral Hydrogen Density (cm^{-3})	Proton Density (cm^{-3})	$\sqrt{\mathrm{LSS}}$	CF	bg (R)
0.15	0.05	0.366	2.26	0
0.15	0.07	0.429	2.18	0
0.20	0.05	0.438	3.28	0
0.20	0.10	0.452	2.42	0
0.20	0.20	0.624	1.91	0
0.25	0.10	0.387	3.23	0

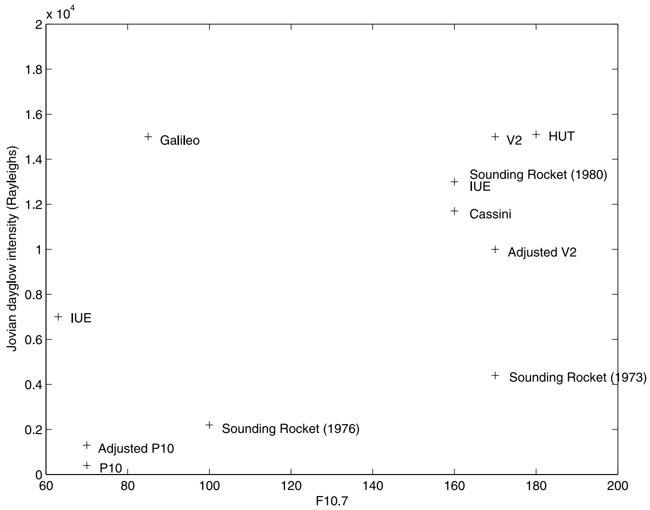

FIG. 2.—Various Jovian Lyα dayglow measurements (in rayleighs; see Table 1) are plotted against the solar 10.7 cm radio flux (F10.7). Both the unadjusted and adjusted *P10* and *V2* data are plotted. The adjusted *P10* value is 3.28 times the old *P10* value, and the adjusted *V2* value is 0.66 times the old *V2* value, where the calibration factors are those for the model with VLISM hydrogen density of 0.2 cm^{-3} and a proton density of 0.05 cm^{-3}. This model was chosen because it best fit the *V2* data.

discrepancy persists for models with a range of neutral hydrogen densities (0.15–0.25 cm^{-3}) and proton densities (0.05–0.2 cm^{-3}) suggests that it would be impossible for a single heliosphere model to accommodate both the very low *P10* downwind intensity and the very high *V2* upwind intensity. This is because a heliosphere model with a very high filtration factor necessary to match the downwind *P10* observation would also lower the calculated upwind intensities, thus worsening the match with the *V2* observation. Similarly, a model with very low filtration necessary to secure a good fit with the *V2* data would severely worsen the match with the *P10* data. Nor would the discrepancy be resolved by allowing for variation of the solar Lyα line shape (Lemaire et al. 1998). Gangopadhyay et al. (2002) showed in their Figure 9 that the ratio of the model intensity to the calibrated 1979–1988 *P10* data declines from about 1.3 to about 0.9 as the solar flux increases. The discrepancy between the calculated intensity and *P10* observation cannot be accounted for even if this trend is due to line-center flux variation since the calculated intensity would change by a maximum of 30%. This decline can also not be due to the gain loss suffered by the *P10* photometer beyond 40 AU since (1) 9 of the 11 *P10* data used here were obtained shortward of 40 AU and (2) the two *P10* data obtained beyond 40 AU have been corrected for the gain loss (Hall et al. 1993).

Finally, it is of interest to see the effect of the revision of calibration of *P10* photometer and *V2* spectrometers on the Jovian dayglow observations. It is clear from Tables 4 and 5 that while *P10* intensity values need to be increased by 1.91–3.28, *V2* intensity values need to be reduced by 0.5–0.76, depending on the neutral model used. This would imply that *P10* observed about 760–1310 R of Jovian Lyα and H_2-band emissions, depending on the VLISM hydrogen density. *V2* observation would then be between 7500 and 11,500 R. These corrections would reduce the dynamic range of the observed brightness in Jupiter, as can be seen from the plot of the Jovian glow measurements by various spacecraft against the solar 10.7 cm radio flux, better known as F10.7 (Fig. 2). There is no clear trend of the Jovian dayglow brightness tracking the F10.7 index even when the adjusted *P10* and *V2* measurements are used. Of course, it was not possible to adjust the measurements of the other spacecraft since there is no intercalibration comparison between these spacecraft and *P10* and *V2*. The fact that the adjusted *V2* measurement is almost a factor of 2 greater than the expected resonance scattering contribution suggests that there must be additional energy powering the Jupiter dayglow.

5. CONCLUDING REMARKS

The work presented here suggests that the resolution of the *P10* and *V2* calibration difference at Lyα is critically dependent on both the VLISM neutral hydrogen density and on the absolute value of the solar Lyα flux. While there has indeed been a recent upward revision of the solar Lyα flux, the VLISM neutral hydrogen density is still not very well known at present. While heliospheric Lyα glow measurements, neutral hydrogen density determinations from solar wind slow-down and pickup-ion data, and *V1* energetic particle measurements support an upward revision of *P10* and downward revision of *V2* intensity values, it is not yet possible to accurately estimate the amount of revision.

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