Magnetic Waves Excited by Newborn Inner Source Pickup H^+ Measured by the Voyager Spacecraft Inside 3AU

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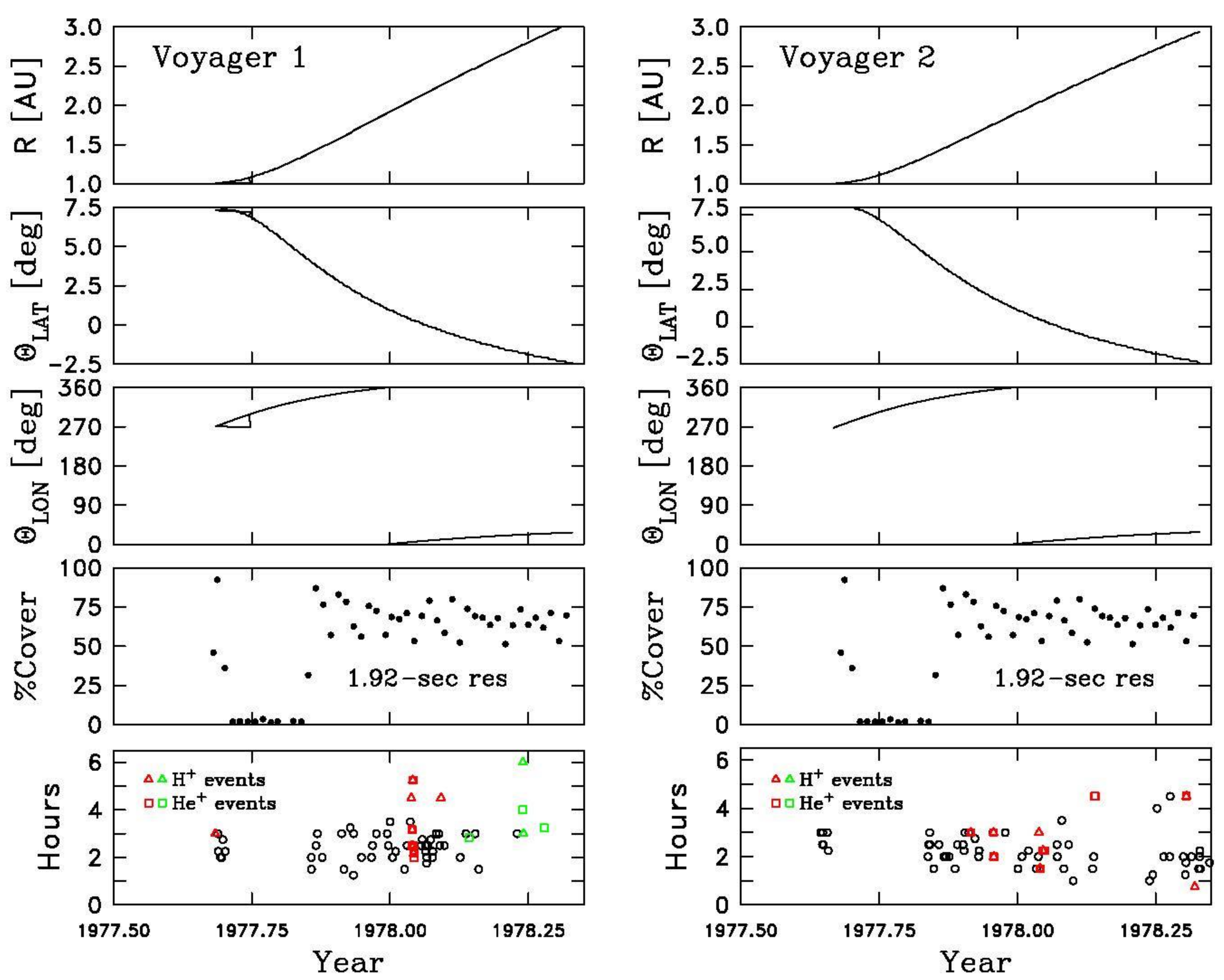
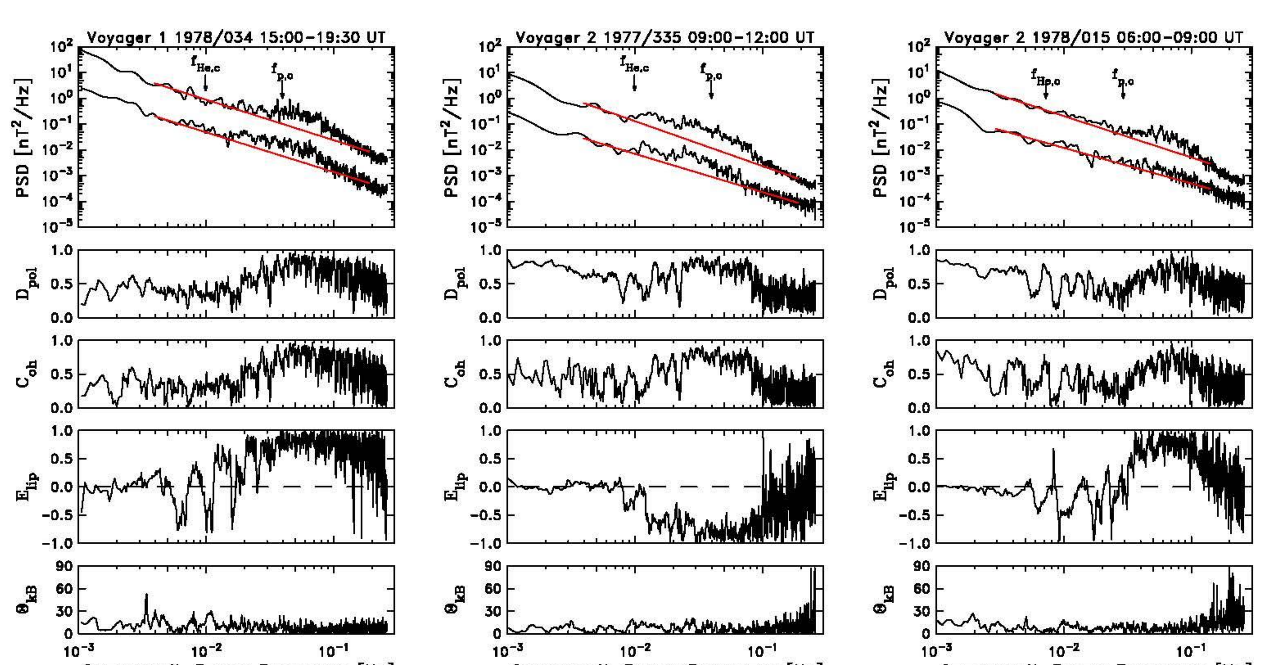
Abstract: In Hollick et al. (2018a,b,c), we surveyed the Voyager magnetic field data from launch through 1990 where the Voyagers 1 and 2 spacecraft reach 43.5AU and 33.6AU, respectively. We identified 637 intervals of wave activity that could be attributed to either interstellar pickup He^+, H^+ or both. In our quest to identify and study low-frequency magnetic waves arising from interstellar pickup H^+, we found 19 intervals, 16 with thermal ion data, within ~ 3AU. We compared the growth rate of the waves with the rate of background turbulence they must overcome to reach observable levels. Ionization of interstellar neutral H is highly efficient resulting in a factor of 10 reduction in density by 1AU relative to values at R > 10AU. At the same time, solar wind turbulence increases with decreasing distance to the Sun. This makes it unlikely that interstellar neutral hydrogen can penetrate within ~ 3AU in sufficient number to explain the wave observations seen by the Voyager magnetometers. We consider the possibility that the so-called "inner source" for pickup H^+ arising from the interaction of solar wind protons with dust grains may account for the density of newborn pickup ions required for the growth of the observed waves. Although the Voyagers lack the instrumentation required to measure pickup ions, we do conclude that the inner source theories provide a compelling explanation for the majority of the observations while it is possible that a few could be due to either interstellar ions or shocks.

Voyager 1 & 2 Trajectories First Year of Flight



(above) Trajectories of the Voyager 1 & 2 spacecraft during the first year of flight. In addition, the percent of coverage is provided. During the first year the Voyagers averaged between 50% and 75% data coverage per day. The bottom panel shows the time and duration of the wave events that are attributed to pickup H^+ (triangles) and He^+ (squares). Red symbols represent times when the thermal ion data (wind speed, density, etc.) are available and green symbols represent those times when they are not.

Examples of Wave Observations due to Pickup He^+ and H^+

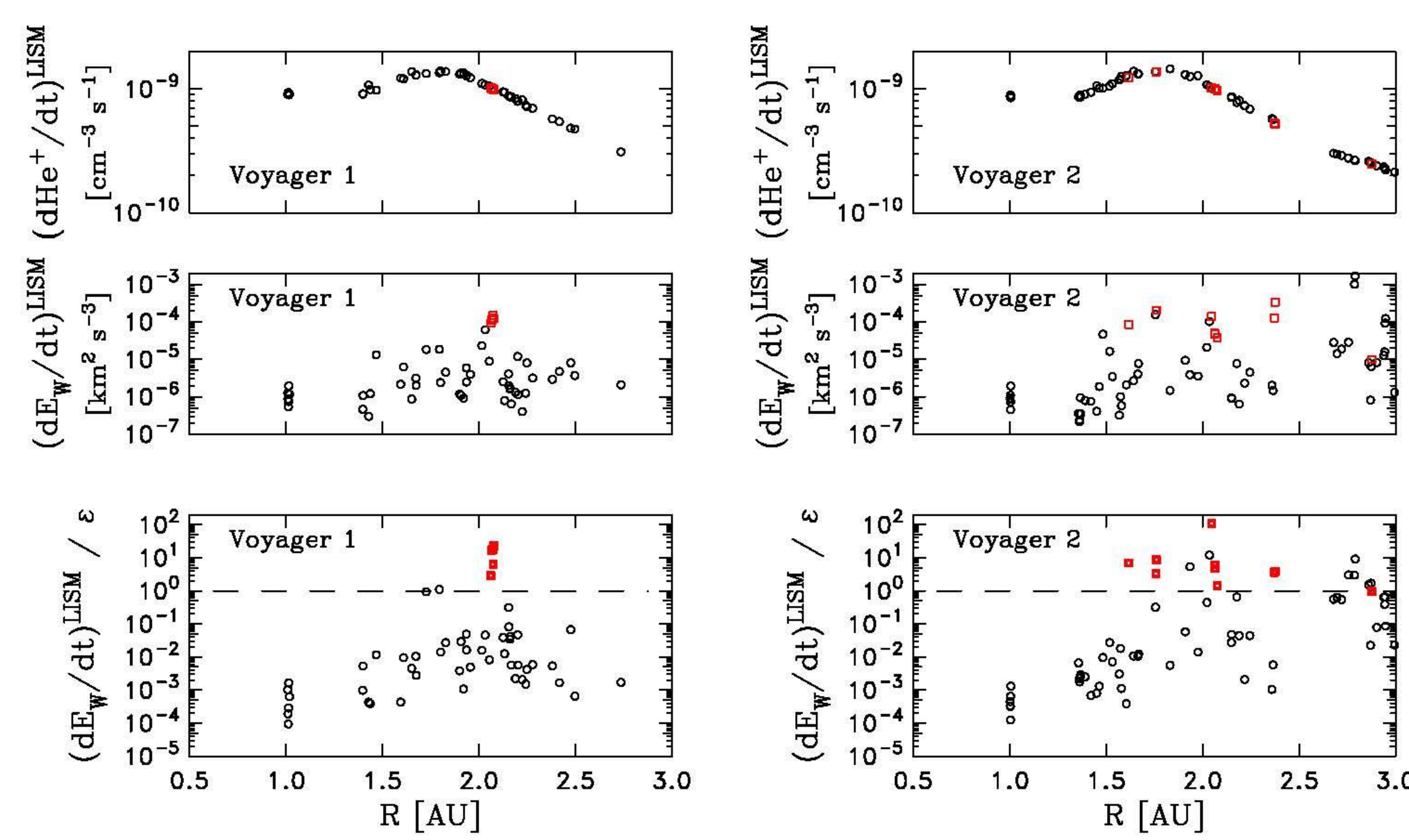


(above) Neutral atoms have very little speed relative to the Sun. LISM neutrals enter the heliosphere at ~ 25 km/s. Once ionized, they are now orbiting the local magnetic field at the solar wind speed. For nearly radial fields, this means that cyclotron resonance with the background magnetic fluctuations produces a wave that is convected past the spacecraft to produce a wave signature at the cyclotron frequency of the source ion. Pitch-angle scattering produces waves at higher frequencies. The waves should be Sunward propagating and right-hand polarized in the spacecraft frame, but left-hand polarization is also seen in all of our studies. The above examples show two cases of waves excited by pickup H^+ only and one example of excitations by both H^+ and He^+.

Ion production rate and wave excitation rate vs turbulence rate for Local Interstellar Medium (LISM) neutrals

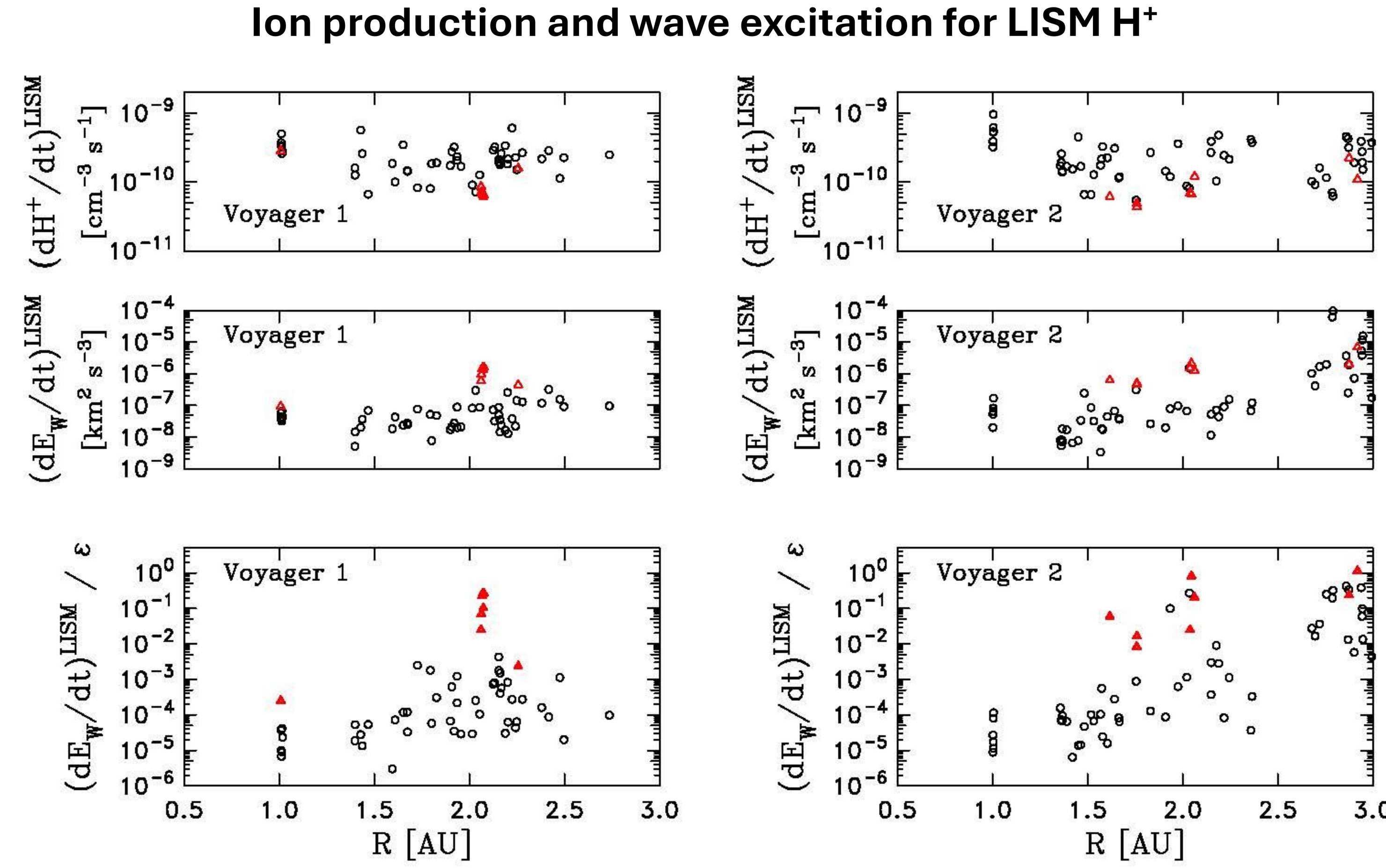
We found 19 wave events during the first year of the Voyager flights when their heliocentric distance was < 3AU. Some showed evidence of excitation by pickup He+ and some by H+ and some by both. The difficulty with the LISM source interpretation is that LISM neutral H density falls exponentially inside 10AU making excitation by LISM H+ unlikely. LISM He^+ reaches the Sun and is gravitationally focused behind it. We compute the rate of pickup ion production using standard published theory and obtain the rate of wave excitation by applying the derivative of the asymptotic prediction of Lee (1982) that does not take turbulence into account. The time required for these growth rates to reach the observed energy levels is significant as the newborn ion production is slow. We assume that each newborn pickup ion undergoes complete scattering to 180°. We then compare that rate of energy growth to the rate of energy transport through the turbulent spectrum to see if wave growth can exceed the rate at which energy is remade by the background turbulence dynamics. In these instances, LISM He^+ is a successful source to explain the observations, but LISM H^+ is not. We show these results below.

Ion production and wave excitation for LISM He^+



(above top) Production rate of He^+ from neutral atomic He originating from the LISM. (above middle) Rate of wave energy excitation by the scattering of newly ionized He^+. (above bottom) Ratio of wave energy production to turbulent remaking of the energy as the turbulent dynamics moves the wave energy to smaller scales for dissipation. Note that during these He^+-excited wave events the LISM source is adequate to produce wave growth that exceeds the turbulence rate meaning that the wave can accumulate energy and grow to observable levels.

Ion production and wave excitation for LISM H^+

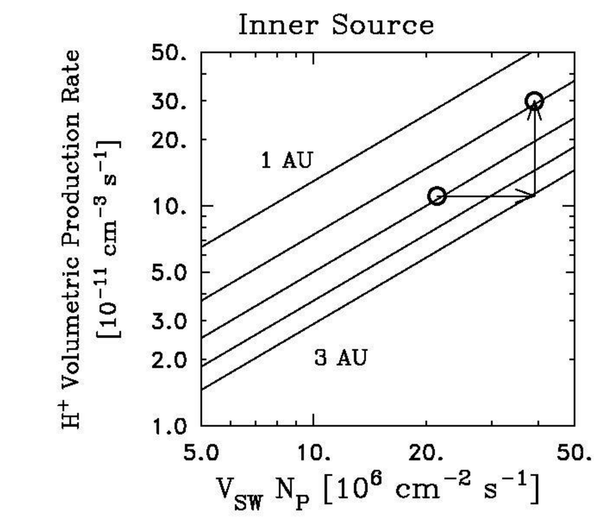


(above top) Production rate of H^+ from neutral atomic H originating from the LISM. (above middle) Rate of wave energy excitation by the scattering of newly ionized H^+. (above bottom) Ratio of wave energy production to turbulent remaking of the energy as the turbulent dynamics moves the wave energy to smaller scales for dissipation. Note that during these H^+-excited wave events the LISM source is generally not adequate to produce wave growth that exceeds the turbulence rate meaning that the wave can never accumulate energy and grow to observable levels.

Inner Source Explanation for the Waves Excited by Pickup H^+

While the generation of pickup ions from LISM neutral atoms is now well-understood, the production of pickup ions from the inner source is not as well understood. We adopt the theory that solar wind protons produce pickup ions by impacting dust grains. Quinn et al. (2018) provides us with a production rate for pickup H+ that depends on both the heliocentric distance and the solar wind flux. We have used these production rates in combination with the spacecraft location and measured solar wind flux to determine a pickup ion production rate that we then use in the same manner as with the LISM source, but we find that the resulting growth rate is still inadequate to overcome the background turbulence as is needed to produce an observable wave signature.

However, there is one distinction between the LISM and inner source that is critical to understanding the excitation of waves – the LISM source is weaker at distances closer to the Sun while the inner source grows stronger. The growth rate for these waves is slow, and the times required to reach the observed wave energy is measured in days rather than minutes. This means that the pickup ion source responsible for the waves lies closer to the Sun. We can build this non-local source idea into the calculations by computing the growth time of the waves, translating the source calculation to a location appropriately closer to the Sun, recomputing the pickup ion production rate, and then recompute a growth rate that we can compare to the turbulence rate.



(above) Pickup ion production rate as function of heliocentric distance and solar wind flux computed for the inner source (Quinn et al. 2018) with a demonstration of the translation required to recover the nonlocal ion production rate.

Minimum Growth Rate Determination

The minimum growth rate required to observe the waves is that the wave energy growth exceed the energy transport rate due to turbulence. We can determine the required rate of pickup ion production using two methods that derive from the instability analysis. The first, MIN1, uses the wave solution with the greatest theoretical growth rate and the second, MIN2, uses the wave that is observed to have the greatest energy enhancement above background. The first is theoretical and the second is observational. We then scale the ion production rate to match the turbulence rate for each case.

Table 4. Voyagers 1 & 2 Pickup H^+ Production Rates

S/C	Year	Time [DOY::Hour:Min]	$(dH^+/dt)^{LISM}$ $[\times 10^{-10} cm^{-3} s^{-1}]$	$(dH^+/dt)^{IS}$	$(dH^+/dt)^{MIN1}$ $[\times 10^{-10} cm^{-3} s^{-1}]$	$(dH^+/dt)^{MIN2}$	$(dH^+/dt)^{IS}_{R-\tau V_{SW}}$ $[\times 10^{-10} cm^{-3} s^{-1}]$
V1	1977	250::18:00-250::21:00†	2.81(3.93)	23.2	2243.	2235.	25.4
V1	1978	015::00:00-015::04:30	0.86(1.20)	1.52	19.5	9.17	4.97
V1	1978	015::06:30-015::09:00	0.72(1.01)	1.14	8.87	4.03	4.90 *
V1	1978	015::13:30-015::16:40	0.69(0.97)	1.03	3.88	2.25	2.48 *
V1	1978	016::00:00-016::05:15	0.64(0.90)	0.89	3.20	1.80	2.46 *
V1	1978	016::06:30-016::09:00	0.60(0.84)	0.78	5.78	3.93	1.57
V1	1978	016::13:20-016::15:30	0.65(0.91)	0.86	3.18	2.09	—
V1	1978	034::15:00-034::19:30†	1.58(2.21)	2.18	202.	132.	3.11
V2	1977	335::09:00-335::12:00	0.34(0.48)	2.73	8.45	5.80	8.91 *
V2	1977	350::07:30-350::10:30‡ ♯	0.49(0.69)	1.54	20.6	9.54	2.16
V2	1977	350::11:00-350::13:00‡ ♯	0.44(0.62)	1.24	12.4	5.51	2.04
V2	1978	015::06:00-015::09:00‡ ♭	0.48(0.67)	1.16	20.4	28.6	1.69
V2	1978	016::00:00-016::01:30	0.46(0.64)	1.02	1.42	0.87	1.82 *
V2	1978	017::20:15-017::22:30	0.84(1.18)	2.16	6.92	5.82	3.23
V2	1978	112::09:00-112::13:30‡ ♯	1.97(2.67)	0.88	11.7	7.51	1.90
V2	1978	118::00:00-118::00:45‡ ♭	0.96(1.34)	0.29	2.01	1.24	0.41

†This event appears to be shock associated.

‡Potentially unexplainable by either interstellar source or inner source ions.

♯Potentially misidentified due to high-frequency extension of He^+ resonance.

♭Clear wave signature at $f_{sc} > f_{p,c}$.

The table (above) shows the results of this analysis. For each wave interval with an H^+ source, we list the time, the H^+ production rate for the LISM source using two current predictions for the interstellar neutral H, the unmodified inner source production rate, the two minimum production rates required to overcome the background turbulence, and the modified inner source rate that accounts for the growth time of the waves. We have concluded that several events are associated with shocks while others may be extensions of the He^+ waves into H^+ frequencies. Only the most distant V2 event can be consistent with the LISM source while 5 events (marked with stars *) are consistent with the modified inner source rate. With the exception of the single V2 event, the inner source provides a stronger ion source for the instability than the LISM.

While we believe that there is ample room for improved theory describing the inner source production of pickup ions and the associated wave excitation, we believe this demonstrates that there is merit to the inner source interpretation.

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