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Detection of a radio emission at 3 kHz in the outer heliosphere

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A radio source in the outer heliosphere has been detected by the plasma wave receivers on Voyagers 1 and 2. The radio emission is observed in the frequency range 2-3 kHz, and is above the local solar wind electron plasma frequency whenever supporting plasma density data are available. The maximum spectral density of the emission recorded is $\sim 10^{-14}\ V^2\ m^{-2}\ Hz^{-1}$. *The bandwidth of the radio noise is* ~ 1 *kHz. Possible sources include continuum radiation from Jupiter's distant magnetotail and radiation at the second harmonic of the plasma frequency at the heliopause. If the latter interpretation is correct, these data represent the first remote observations of the heliopause.*

THE Voyager 1 and 2 spacecraft are currently sampling the interplanetary environment at heliocentric radial distances of 19 and 13 AU, respectively. Since the Saturn encounters in 1980 and 1981, the plasma wave data have shown very little activity in the outer heliosphere. The primary waves observed include occasional electron plasma oscillations and ion-acoustic waves, sometimes detected in association with interplanetary shocks. Figure 1*b* shows the trajectories of Jupiter, Saturn, Uranus and Voyagers 1 and 2 for the interval 30 August 1983 to 21 February 1984; during this time a radio emission near 3 kHz was being detected by the plasma wave instruments on both Voyagers. Figure 1*a* shows a meridional view of the outer planets and the trajectories of the two Voyagers. In this view, the abscissa is in the ecliptic plane and the positions of the various planets and spacecraft have all been rotated into the same plane.

The observations discussed here were obtained on both Voyager spacecraft using identical plasma wave receivers which measure the electric field component of plasma and radio waves in the frequency range 10 Hz to 56 kHz by the use of 16-channel spectrum analysers and wideband receivers with passbands of 40 Hz to 12 kHz (ref. 1).

Observations

During the period from 30 August 1983 to the present, a very weak signal has been apparent in the 3.11-kHz channel of the Voyager 1 plasma wave instrument. The 3.11-kHz data for a 6-month interval are plotted as a function of time in Fig. 2. Each point in Fig. 2 represents a 51.2-min average of the electric field spectral density in the 3.11-kHz channel. It is apparent that after about day 242 (30 August) 1983 a smoothly varying signal was continuously present. Amplitude variations within the 51.2-min averaging intervals were small compared with the long-term variations seen in Fig. 2. Beginning at about day 292, the variations appear to be quasi-periodic with a period of about 26 days. This is close to the sidereal period of the Sun, hence, we suspect the solar wind may be responsible, in part, for the amplitude variations. There also seems to be a gradual overall variation in the amplitude of the emission with a rise from the onset near day 242 to the peak near day 285 and a subsequent decrease in amplitude towards the end of the plotted interval. During this entire time interval, no signal was detected in the 5.62-kHz channel. For a few one- or two-week periods a much weaker emission could be seen in the 1.78-kHz channel.

Several times during the interval plotted in Fig. 2, the wideband channel of the Voyager 1 plasma wave receiver was interrogated. For each wideband interrogation, four contiguous 48-s 'frames' of plasma wave data with high temporal and spectral resolution were obtained. In each wideband frame transmitted after day 242 1983, a weak band of emission near 3 kHz could be seen. Table 1 summarizes the wideband observations of the 3-kHz emission by both Voyager spacecraft. SCET is the spacecraft event time for each wideband observation and f_0 and f_{min} are the frequencies of the peak of the emission and the low-frequency cutoff, respectively. The electron plasma frequency as determined by the Plasma Science instrument (J. W. Belcher, personal communication) is labelled f_p.

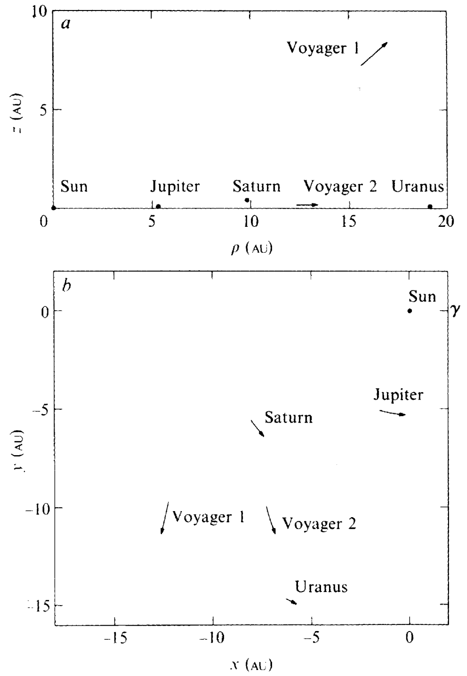

Fig. 1 The trajectories of Jupiter, Saturn, Uranus, and Voyagers 1 and 2 during the interval 30 August 1983 to 21 February 1984 when the Voyager 1 plasma wave receiver was detecting a new radio emission in the frequency range 2-3 kHz. Evidence from Voyager 2 indicates the radio emission may have been observable from that vantage point over a similar interval. *a*, The positions of the outer planets and the Voyager spacecraft rotated into a single meridian plane with the ρ-axis lying in the ecliptic plane. *b*, The projection of the trajectories of the same bodies in the ecliptic plane with the *x*-axis pointing in the direction of the first point in Aries, γ.

An example of one of the wideband frames is shown in Fig. 3 in the format of a frequency-time spectrogram where the amplitudes of waves are plotted as a function of frequency and

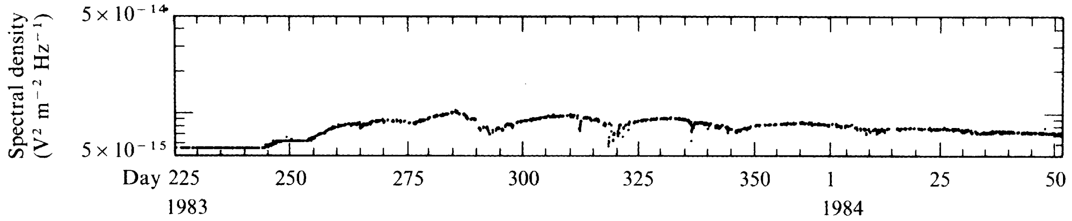

Fig. 2 Electric field spectral densities from the Voyager 1 3.11-kHz plasma wave receiver channel plotted as a function of time for slightly more than six months. Each point represents a 51.2-min average. The radio emission first appeared on day 243 1983.

time. The most intense waves are black. In Fig. 3, the intense tones at frequencies below 1 kHz are interference from the operation of the onboard tape recorder used to record the wideband data. The very narrow tones at 2.4 and 4.8 kHz are the first and second harmonics of the spacecraft power supply.

The diffuse noise seen between 2 and 3 kHz is the emission which accounts for the signal received in the 3.11-kHz channel plotted in Fig. 2. This spectrogram is typical of the others received since day 242 1983, except for variations in the signal strength and minor variations in the lower frequency cutoff of the emission. The data from a 4-s interval in the spectrogram in Fig. 3 were averaged to form the spectrum shown in Fig. 4*a* which illustrates the detailed structure of the emission band. The power supply interference tone at 2.4 kHz, which rises out of the middle of the emission band, and a notch filter which serves to limit the power supply interference, cause some difficulty in the interpretation of the spectrum in Fig. 4. The gap in the spectrum at 2.4 kHz may be due to the notch filter, but we cannot rule out the possibility of a complex spectral structure which is inherent in the radio emission itself.

The Voyager 2 3.11-kHz channel sensitivity is not as great as that on Voyager 1 because of a partial failure in the Voyager 2 Flight Data System which occurred shortly after launch. Hence, at these low wave amplitudes we do not see any response in the Voyager 2 spectrum analyser channels. On the other hand, wideband frames obtained from Voyager 2 (which are unaffected by the Flight Data System failure) show a feature which is very similar to that shown in Fig. 3 (see Table 1). The earliest Voyager 2 wideband frame showing evidence of the emission was obtained on day 257 (14 September) 1983 when the spacecraft was 12.7 AU from the Sun. Samples showing evidence of the emission were also obtained on days 294, 307, and 339 of 1983 and day 3 of 1984. Because no wideband frames were obtained on Voyager 2 between day 228 (when the emission was not seen in the wideband data) and day 257, it is possible that the signal has been continuously present at Voyager 2 since about day 243 as was the case for Voyager 1. This close correspondence in onset times observed at two locations separated by nearly 10 AU suggests the two spacecraft are detecting a temporal change as opposed to a spatial variation.

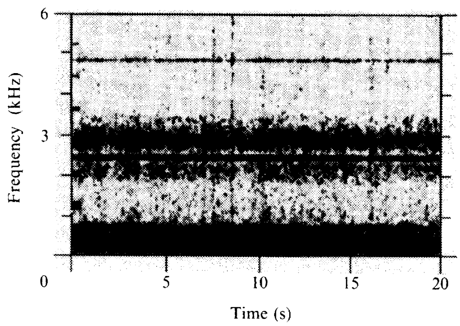

Fig. 3 Spectrogram showing the intensity of waves as a function of frequency and time for a 20-s interval. The diffuse emission seen between 2 and 3.5 kHz is the new radio emission reported here. The narrowband tones at 2.4 and 4.8 kHz as well as below about 800 Hz are spacecraft interference. Start time 2021: 52 SCET of day 307, 1983; $R = 17.9$ AU; celestial lat. = 25.5°.

Figure 4*b* shows a spectrum taken on day 307 by the Voyager 2 plasma wave instrument. The receiver threshold is not quite as low as in the case of Voyager 1, but the similarity between the emission just below 3 kHz with the feature shown in Fig. 4*a* can be readily seen. Note that the amplitude of the emission is nearly identical to the emission observed by Voyager 1.

The Voyager 2 observations of the emission are important in our identification of the emission as a radio signal because the plasma instrument[2] on Voyager 2 can provide a measure of the local electron density, hence, plasma frequency. (The Voyager 1 plasma instrument has not functioned since shortly after the Saturn encounter.) If the emission is a freely propagating radio emission, then it must lie above both the electron plasma frequency and gyrofrequency. For four of the five days when wideband data are available, a determination of the density from the plasma instrument yielded values ranging from 0.02 to 0.04 cm^{-3} as shown in Table 1 (J. W. Belcher, personal communication). The respective plasma frequencies range from 1.3 kHz to ~1.8 kHz because $f_p(Hz) = 8{,}980\sqrt{n_e}$, where n_e is the electron density in cm^{-3}. For days 257, 307, and 339, the values for f_p are obtained from the 3-min determination of n_e made closest to the wideband frames and have errors of ~10%. No reliable measurement is available for day 284 and the value for day 3 of 1984 is a daily average used in the absence of detailed analyses which are not yet completed. The low-frequency cutoff of the emission ranged from ~2 to nearly 3 kHz over the five intervals of wideband data. In each case, the emission exhibited a low-frequency cutoff which was well above the local electron plasma frequency. As the emission lies above f_p and the electron gyrofrequency in the solar wind is much less than f_p, the emission meets a necessary condition for being a freely propagating radio wave. It is easy to speculate that the periodic dips in the emission amplitude seen in the Voyager 1 data plotted in Fig. 2 are due to the passage of relatively high-density structures in the solar wind associated with high-speed streams which shield the spacecraft from the source of emission.

With the available data, it is not possible to confirm that the emission is a freely propagating radio wave; however, we can eliminate local plasma phenomena with a high level of confidence. There are two types of local (non-propagating) phenomena which have been observed at, or above, the local plasma frequency in the solar wind. The most familiar waves

Table 1 Wideband waveform observations of 3-kHz radio emissions

Year	Day	SCET	f_0 (kHz)	f_{min} (kHz)	f_p (kHz)
Voyager 1					
83	283	1407	2.8	1.9	NA
83	307	2022	2.9	1.8	NA
83	339	1720	3.0	1.9	NA
84	3	1619	3.0	2.1	NA
Voyager 2					
83	257	1940	3.0	2.7	1.4
83	284	1452	2.8	1.9	NA
83	307	1633	2.8	2.0	1.3
83	339	1747	3.0	2.6	1.3
84	3	1805	3.1	2.7	1.8

NA, not available.

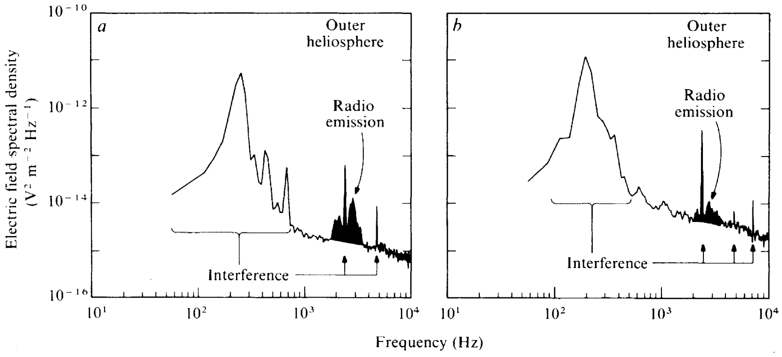

Fig. 4 *a*, 4-s average spectrum taken from the spectrogram shown in Fig. 3 at 2021: 56 SCET. The shaded portion of the spectrum corresponds to the new emission. Note that the interpretation of the spectrum is complicated by the existence of a notch filter and power supply tone centred at 2.4 kHz. *b*, A 4-s average spectrum of the 3-kHz radio emission observed by Voyager 2 at a time (1632: 05 SCET) very close to when the emission shown in *a* was observed by Voyager 1. Note the similar amplitude of the features near 3 kHz in *a* and *b*.

in this frequency regime are electron plasma oscillations or Langmuir waves. The observed waves are almost certainly not plasma oscillations as the bandwidth of the observed emission is much larger than that for plasma oscillations, particularly at low amplitudes and plasma oscillations are characterized by a very sporadic temporal character. The observed emission shows only very smooth variations in amplitude with time.

The second type of local phenomena which might be considered are quasi-thermal electrostatic plasma waves[3]. Hoang *et al.*[3] discuss the spectral form of the thermal plasma emission in detail for both long and short (compared with the Debye length) antennas. For the typical solar wind observed in this epoch by the two Voyagers, the density is 0.05 cm^{-3}, hence, even with a temperature as low as 1 eV, the Debye length is >30 m, compared with an effective antenna length on the two Voyagers of 7 m. Therefore, the short antenna results of Hoang *et al.* are relevant to this discussion. The quasi-thermal plasma noise detected by a short antenna has a power law spectrum with an index of −1.5 and shows no peak and no cutoff at f_p. The spectra shown in Figs 3 and 4 exhibit both a low-frequency cutoff and at least one peak. These waves, therefore, are clearly not the thermal electrostatic waves discussed by Hoang *et al.*[3].

Table 1 also shows that the frequency of the peak in the emission is nearly the same at both spacecraft despite the relatively large variations in local plasma conditions which would be expected between two points separated by ~10 AU. The nearly constant frequency would not be expected if the emission were a local effect. Finally, the fact that Voyagers 1 and 2 both began detecting the 3-kHz emission at about the same time despite being nearly 10 AU apart argues strongly for a freely propagating radio emission and against a local plasma phenomenon.

Possible sources

Several possible sources exist in, and beyond, the outer heliosphere for the radio emission reported here. The emission is most reminiscent of continuum radiation trapped in Jupiter's distant magnetotail because it lies in a very similar frequency range. Figure 5 shows an example of the continuum radiation observed 2,019R_J downstream from Jupiter[4], where R_J is the radius of Jupiter. Given that the continuum radiation is confined to the tail cavity by the surrounding high-density solar wind close to Jupiter and also given the geometry of the observations presented in Fig. 1, it is clear that the emissions would have to propagate down the jovian tail to a point where the waves are at a frequency greater than the surrounding solar wind plasma frequency. Having reached this 'window' they could subsequently propagate freely and possibly escape in the direction of the Voyager spacecraft.

However, a comparison of the two spectra from the outer heliosphere in Fig. 4 with that in Fig. 5 taken in Jupiter's tail suggests that the two emissions have different sources. The spectrum of trapped continuum radiation varies as $f^{-\alpha}$ where α ranges between 3 and 6 (ref. 5). The radiation in Fig. 4 clearly does not show that type of frequency dependence. Moreover, the other waveform samples from both Voyagers of the new radio emission do not deviate greatly from the form shown in Fig. 4. Hence, to identify the spectra in Fig. 4 with jovian continuum radiation, one would have to rely on the solar wind medium to reshape the spectrum. The general consistency of the recently obtained spectra is inconsistent with such a shaping process.

An analysis of the amplitude of the new emission also argues against a jovian source. If the continuum radiation escaping from the tail of Jupiter were to be emitted from some point along the tail (assumed to extend in the anti-solar direction from Jupiter), one would expect to see an approximate R^{-2} dependence in the intensity of the emission from the exit 'window'. From Fig. 1, we see that Voyager 1 and 2 are about 14.8 and 6.4 AU from the jovian tail axis, respectively; hence, one would expect a signal more than a factor of 5 times larger at Voyager 2 than at Voyager 1, but waveform samples taken on both spacecraft on 3 November (shown in Fig. 4) indicate that the spectral density at the peak of the emission band is nearly identical at both spacecraft. (We have used a calibration technique similar to that used by W.S.K. *et al.*[5] which avoids the Voyager 2 calibration uncertainty.) Also, the intensity of the Voyager 1 spectrum obtained at 18 AU is only a factor of about 3 less than that obtained only 2,019R_J (~1 AU) downstream from Jupiter. Hence, it seems difficult to understand the emission as jovian in origin on the basis of intensity.

We have also performed a power spectrum analysis on the data presented in Fig. 2 to look for variations near the rotation period of Jupiter since some of the radiation detected in the distant jovian tail shows amplitude fluctuations with a period of about 10 h (ref. 6). No periodicity near 10 h was detected.

Thus, while Jupiter initially seems a likely source for the emission on the basis of the frequency of the emission, the spectral shape, the lack of spatial variation in amplitude, and the lack of 10-h periodicities cast serious doubts on this interpre-

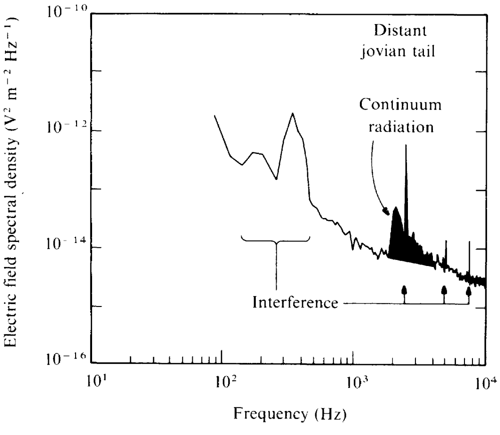

Fig. 5 A 4-s average spectrum of continuum radiation trapped in the jovian tail 2,019R_J downstream from Jupiter (shaded portion) obtained by Voyager 2 on 1 February 1980 at 0016: 26 SCET. Notice that this emission is sharply peaked at lower frequencies in contrast to the emission shown in Fig. 4.

tation. Below, we examine other possibilities for the source of the emission.

Continuum radiation trapped within Saturn's magnetosphere has also been detected[5]. Although the position of Voyager 1 might seem to be ideal to detect such saturnian radiation when one examines only the ecliptic plane projection in Fig. 1*b*, Fig. 1*a* shows that the spacecraft was actually 8 AU north of the ecliptic; hence, it is difficult to understand how any radiation from Saturn could propagate to either of the spacecraft. Moreover, as with Jupiter, the saturnian continuum radiation spectrum does not match the spectra in Fig. 4. In addition, the saturnian radiation is even weaker than Jupiter's, thus, we conclude that Saturn is not a likely source for the newly detected radio emission.

Uranus is another possible source for the radiation as we do not know what radio emissions from Uranus might look like. Using observations of the Earth, Jupiter, and Saturn as guides, the upstream planetary radio emission which most closely resembles the new emission is escaping continuum radiation from the Earth[7,8] and Jupiter[9]. The escaping continuum radiation from those planets is extremely weak, however, and even if Uranus had similar emissions, they could not be detected by either Voyager spacecraft at their present distances unless the source was extremely bright. Other types of planetary radio emissions are intrinsically more intense than the continuum radiation; their dynamic spectra, however, are more highly structured than the emissions reported here. Nevertheless, we cannot rule out Uranus as a source of the radio noise reported above until the Voyager 2 encounter with that planet in 1986, although, we now feel that Uranus is not a likely source.

It is possible that the new radio emission detected by Voyagers 1 and 2 is generated outside the heliosphere. With our lack of information about the region, particularly at such low frequencies, any number of sources might be contemplated. Once such source is a fast pulsar which might emit enough energy at low harmonics of its pulsing rate to be detected in the frequency range of a few kHz. However, we suggest that the broad bandwidth of the newly detected signal is sufficient to rule out pulsars as the source. In addition, the power flux of the band shown in Fig. 4*a* integrated over the 1-kHz bandwidth is of the order of 10^{-14} W m^{-2}. The radio luminosity of the Crab Nebula integrated over a bandwidth of 10^8–10^9 Hz is about 10^{31} erg s^{-1} (ref. 10), hence, at a distance of ~1 kpc this corresponds to 10^{-16} W m^{-2}, much less than the value observed by the Voyager spacecraft. (An equivalent, but alternate comparison, is to calculate the power spectral density from the Crab assuming the 10^{31} erg s^{-1} is emitted in a 1-kHz bandwidth. This would be about 10^{-19} W m^{-2} Hz^{-1} compared with a value of 10^{-17} W m^{-2} Hz^{-1} observed by Voyager.) It is interesting to think of what other sources of radio noise lie beyond the Solar System, but perhaps fruitless to speculate on them at this point.

We have considered one other possibility for the source of the radio emission: the heliopause, itself. It is reasonable to assume that there is a supersonic shock marking the heliopause (sometimes referred to as the terminal shock) and shocks are known to be the source of weak, relatively narrowbanded radio noise. Specifically, Dunckel[11], Gurnett[12] and Hoang *et al.*[13] have all reported radio emissions at $2f_p$ emanating from the vicinity of the Earth's bow shock and a similar phenomenon has been reported near an interplanetary shock[4]. Theories for the emission at $2f_p$ have been offered by Fung *et al.*[14] and Cairns and Melrose[15]. The fact that this type of emission is quite weak is countered by the large source size of the heliopause and resulting large solid angle as seen by an observer in the outer heliosphere. The smoothly varying temporal character and bandwidth of the new emission are consistent with the $2f_p$ model.

If, indeed, the heliopause is generating the radio emission at $2f_p$, some interesting statements can be made concerning the size of the heliosphere. This scenario implies that the plasma frequency at the heliopause is half of 3 kHz, or 1.5 kHz; n_e at the heliopause is then ~0.03 cm^{-3}. One can expect a maximum jump in the density at the shock of a factor of 4 (and we also assume the interstellar density is higher than just inside the heliopause), meaning the density just inside the heliopause could be as low as 0.008 cm^{-3}. This corresponds to a plasma frequency of about 780 Hz. Because the density in the solar wind falls as $1/R^2$ (assuming constant solar wind speed) and the plasma frequency is proportional to $\sqrt{n_e}$, the plasma frequency varies as $1/R$. Given that f_p is ~2 kHz at 18 AU (using Fig. 3) and that it drops to 780 Hz at the heliopause, it is easy to solve for the radial distance of the heliopause, that is ~46 AU.

Obviously, the reasoning above assumes no variations in the solar wind density as a function of time and is subject to several simplifying assumptions. Also, if one assumes the density in the interstellar medium is less than just inside the heliopause, the minimum f_p in the heliosphere is 1.5 kHz and Voyager 1 is very close to that point. Taking the value of 46 AU (with liberal error bars), however, we can compare it with other predictions of the distance to the heliopause. One popular method is to interpret the cosmic ray gradient to arrive at a distance to the boundary. One such prediction of >65 AU by Webber and Lockwood[16] was based primarily on Pioneer 10 observations. As Voyager 1 is travelling more or less antiparallel to the interstellar wind flow and Pioneer 10 is headed in nearly the opposite direction, it is commonly assumed that the heliopause will be encountered at smaller heliocentric radial distances by Voyager 1, hence, 46 AU does not seem to be unreasonable. Voyager 1 will be at a distance of about 46 AU in 1991 and perhaps only then will we be certain of the source of this new radio emission.

Conclusion

Voyager 1 and 2 observations of a very weak signal in the range 2–3 kHz in the outer heliosphere at distances of 13–19 AU appear to be evidence of a newly discovered radio emission. While the frequency of the radio emission is similar to continuum radiation in the distant jovian tail, other observations are inconsistent with Jupiter as a source. One other possible candidate for the emission source is $2f_p$ radiation from the heliopause. This is a most exciting possibility, because if this is the case, these observations are our first glimpse of the edge of the heliosphere.

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