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Interplanetary scattering effects in the jovian bKOM radio emission observed by Ulysses

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Abstract. The scattering of radio waves by the interplanetary medium (subsequently referred to simply as 'scattering') imposes limitations on measurements of fine temporal and angular structure at low radio frequencies. The jovian broad-band kilometric radiation (bKOM) is highly structured and observations of this emission, by the Unified Radio and Plasma Experiment (URAP) on board ULYSSES, have been used to study scattering at extremely low frequencies. Structures observed in the bKOM during 1995-6, when the spacecraft was at distances greater than 5 AU from the planet, are compared with observations made in 1991 when the spacecraft was relatively close to Jupiter ($\sim$ 1 AU). Measured values of the e-folding time are compared with theoretical values of temporal broadening and with solar wind electron density measurements made by the SWOOPS experiment on Ulysses. In general, we find that temporal broadening increases with source-observer distance and decreasing frequency, as expected from standard broadening theory, although a few inordinately low values were also observed at distances of 5 to 7 AU. At frequencies close to 45 kHz, an upper limit of about 8 min is clearly visible in observations of the temporal broadening made about 1 AU from Jupiter. Average values of the e-folding time at these same frequencies show a well-defined increase with distance from Jupiter of about 8 min AU^{-1}. We interpret this as 'saturated scattering,' where all ray paths between source and observer are explored, giving an upper limit to the temporal broadening which the medium can introduce. These observations establish limits for scattering in the interplanetary medium (IPM), which are relevant to all low frequency radio observations.

Key words: ???

1. Introduction

Electron density irregularities in the interplanetary medium (IPM) generate variations in refractive index, scattering originally parallel rays originating from a distant source along a range of paths of different lengths. The signal received from the source therefore shows both angular and temporal broadening, well modelled by wave propagation theory (e.g., Rickett 1990).

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Fig. 1. Flight path of Ulysses from launch to the beginning of 1997 with the orbital path of Jupiter for the same period. The beginning of each year is indicated by $*$ for Ulysses and $+$ for Jupiter.

Steinberg et al. (1985) used ISEE-3 observations of interplanetary type III bursts to measure source sizes at frequencies $\leq$ 300 kHz. They found that the source sizes expand with decreasing frequency to 'fill a cone' whose apex is at the Sun. This was interpreted as an observation of the scattering screen rather than the original source. The observed source sizes were found to be correlated with the local plasma density measured at ISEE-3 which was then in an elliptical halo orbit about the L1 point, 235 Earth radii from the Earth on the Sun side. Cairns (1995) has studied scattering effects in 2-3 kHz radiation observed by Voyager beyond 10 AU and believed to be generated in the outer heliosphere. Significant angular broadening is predicted based upon extrapolation of scattering theory close to 1 AU. In the present paper, we use observations of Jupiter made by URAP to study scattering from a source at distances greater than 5 AU in the anti-solar direction, when Ulysses was at about 1.5 to 3.4 AU from the Sun.

The URAP experiment has been described in detail by Stone et al. (1992a), and observations close to Jupiter are reported by Stone et al. (1992b). ULYSSES approached Jupiter from a jovicentric declination of about 1.5° (Fig. 1), passing briefly into an extreme northerly declination before entering a southerly declination close to $-38°$ after encounter. The spacecraft then continued to south solar polar pass in June–October, 1994, and crossed the plane of the ecliptic into a northerly heliographic latitude in March, 1995.

A number of jovian bKOM events were observed during 1995 and 1996, when the spacecraft was at distances greater than 5 AU from the planet. In some of these events, e-folding times (defined here as the time for the bKOM intensity to drop by a factor e from its maximum value) could be measured within a frequency range of about 150 to 35 kHz. Here, we compare these measurements with theoretical broadening values and with solar wind electron density measurements made

Fig. 2. Predicted temporal broadening from a thin screen, using small angle approximations. (a) Kolmogorov (dashed line) and (b) Gaussian (solid line) spatial power spectra.

by the SWOOPS Experiment (Bame et al. 1992; Phillips et al. 1995).

It has not been possible to check the theory experimentally in the past as there was no situation where the source distance and the electron content of the intervening medium were known. The jovian bKOM is highly structured and Ulysses URAP observations of the emission offer the possibility of addressing this problem, albeit approximately. A preliminary report of this work was presented at the 1996 Planetary Radio Emissions Workshop IV, Graz (Barrow et al., 1997).

2. Interplanetary scattering

Extreme scattering effects in the interplanetary medium have been reviewed by Woan (1997) as part of a feasibility study for a radio telescope on the far side of the Moon to operate at frequencies below 30 MHz. A full understanding of the scattering phenomenon can only be gained by modelling the diffactive propagation of waves through the turbulent IPM. However, when the scattering is strong (that is when the Fresnel scale at the scattering medium is greater than the field coherence scale at the observer) important results from the wave model approximate to those from simple geometric refraction (Hewish 1989). This is the case for the inner IPM at frequencies below several tens of megahertz.

A Kolmogorov power law model of the spatial density spectrum in the IPM predicts temporal broadening scaling as $\tau_{\rm b} \propto \nu^{-4.4}$, where ν is the radiation frequency (Rickett 1977). However, there is good observational evidence for a deviation from this power law on spatial scales of 10 to 100 km (e.g., Cohen et al. 1967; Readhead, Kemp & Hewish 1978; Harmon & Coles 1991) making a Gaussian spectrum more appropriate for these observatons, and resulting in a temporal broadening that scales as $\tau_{\rm b} \propto \nu^{-4}$ (Rickett 1977). There is little observational evidence to confirm the validity of either scaling relation at very low frequencies, but it is often assumed that the broadening seen by an observer 1 AU from the Sun along a line of sight with solar elongation $\sim 90^\circ$, will increase with decreasing observing frequency as $\tau_{\rm b} \simeq 0.1\nu^{-4.4}$, where ν is the observing frequency in megahertz and $\tau_{\rm b}$ is in seconds. This is shown in Fig. 2 (dashed line) and assumes not only a Kolmogorov model for the spectrum of density inhomogeneities in the solar wind but also small scattering angles. Thus, intrinsic fluctuations in source flux density on time-scales of less than 5 ms could not be seen at the Earth at frequencies below about 2 MHz. At still lower frequencies, the small angle approximations used to derive the relation are no longer valid and simple arguments indicate that, at some frequency below about 150 kHz at 1 AU, $\tau_{\rm b}$ should attain a limiting value approximately equal to the light travel time between the source and the observer.

2.1. Analysis

At frequencies below a few tens of megahertz, the combined effect of refractive index variations over spatial structures in the IPM is sufficient to introduce random phase variations much greater than one radian across a propagating wavefront. Under these conditions we are able to treat many scattering effects geometrically and consider the effect of the medium on the local normal to the wavefront. The simplest analysis is due to Booker et al. (1950) applied to the Earth's ionosphere, but the approach is equally applicable to modelling the IPM when scattering is strong.

It can be shown (e.g., Thompson et al. 1986; Lyne & Graham-Smith 1990) that density variations, $\Delta n_{\rm e}$, in a thin screen within the IPM corrugate an otherwise plane wavefront so that a point source seen through the screen appears scattered to an rms angular size of

$$\theta_{\rm s} \simeq \left(\frac{D}{a}\right)^{1/2} r_{\rm e}\Delta n_{\rm e}\lambda^2 \ , \tag{1}$$

where $r_{\rm e}$ is the classical radius of an electron, λ the observing wavelength, D the screen thickness and a the scale-size of the irregularities (that is the characteristic width of the distribution, here assumed to be Gaussian). The assumption of a scale-size may appear to be overly restrictive but more sophisticated models based on a Kolmogorov power-law spectrum for the density irregularities give very similar results down to about 200 kHz, except that $\theta_{\rm s} \propto \lambda^{2.2}$ (Rickett 1977). The Kolmogorov model leads to the classical $\nu^{-4.4}$ relation stated above, while the Gaussian model (below) gives $\tau_{\rm b} \propto \nu^{-4}$ (Fig. 2, solid line). Both forms of the relation assume that only small scattering angles are involved, so setting a low-frequency limit to the validity of each relation. In the following analysis, for simplicity, we consider only the Gaussian thin-screen model.

The effect of the scattering screen on temporal structure in the radiation follows directly from the angular broadening identified above. Rays from a source at infinity, scattered by the screen through an angle $\theta_{\rm s}$, will take an extra time

$$\tau = \frac{z\theta_{\rm s}^2}{2c} \tag{2}$$

to reach the receiver relative to an unscattered ray. Here z is the distance between the receiver and the screen, c is the speed of light and the scattering angle is assumed small, so that $\tan\theta_{\rm s} \simeq \theta_{\rm s}$. A radio pulse entering the medium will therefore emerge convolved with a function of characteristic width τ and structure on much finer temporal scales will be lost.

In the thin-screen case, Cronyn (1970) showed that the intensity profile, $I(t)$, of a broadened pulse is

$$I(t) \propto \exp(-t/\tau) \ , \tag{3}$$

i.e., a truncated exponential with $I(t<0)=0$ and decay time of τ (Fig. 3a). In this case the e-folding time of the structure, $\tau_{\rm b}$, is equal to τ.

The more difficult problem of a thick strongly scattering screen was first tackled in a series of papers by Williamson

Fig. 3. (a) pulse profile predicted by Eqn. (3) and (b) pulse profile predicted by the Williamson model and a 1 to 2 AU screen.

(1972, 1973, 1974) in the context of pulse broadening in pulsars by the interstellar medium (ISM). Williamson found that a pulse travelling through a thick scattering screen emerged with a profile having a more gentle rise than in the thin-screen case, but still with an approximately exponential decay.

In the case of jovian emission, we are concerned with scattering in the IPM rather than in the ISM, but the results are entirely applicable. As the plasma number density of the IPM falls off roughly as R^{-2}, where R is the distance from the Sun, and because the Ulysses observations were carried out with the spacecraft between the Sun and Jupiter, we are particularly concerned with Williamson's solution when the scattering medium is uniform but close to the observer rather than uniformly distributed between observer and source. If, as an example, we consider the situation in which Jupiter is in the antisolar direction, the amount of temporal broadening of a jovian signal from material at a distance z from the spacecraft is $\propto z\theta_{\mathrm{s}}^2 \propto z\Delta n_{\mathrm{e}}^2 \propto z/(R_0+z)^4$, where R_0 is the distance of the spacecraft from the Sun. We also assume that the result $\Delta n_{\mathrm{e}} \propto n_{\mathrm{e}}$, shown to be true for the quiet solar wind at higher radio frequencies, holds on spatial scales appropriate here. This function peaks strongly at $z = R_0/3$ and so, to reflect this distribution, we will crudely model the number density of the IPM in the antisolar direction as uniform from 1 to 2 R_0 and zero thereafter. Provided that the Sun, the spacecraft and Jupiter are roughly aligned, the exact geometry is not critical to the general shape of the response function. The form of a broadened pulse after passing through this example model is shown in Fig. 3b.

Note that these standard scattering results were established in the context of signals received at the Earth at much higher frequencies than we are considering here. The time axis scales as $t/\tau \propto \lambda^4$, so long wavelength signals are broadened over considerable time periods and, at frequencies below about 150 kHz seen from the Earth, there will a limit to the temporal broadening as the scattering angle increases. For observations made by Ulysses, we would expect this limit to occur at lower frequencies, whenever the scattering disc associated with the source is greater than about 30°.

These large scattering angles will make the radiation appear to come from most of the sky. However, the longer scattering paths will be attenuated by inverse-square losses and the effective limit to the temporal broadening will approximate to the light travel time between the source and the observer, i.e., about 8.3 min for 1 AU. In the interplanetary medium, for an observer at 1 AU, this restricts the validity of a λ^4 law to frequencies greater than about 150 kHz. A rigorous analysis for signals scattered over these large angles has never been attempted although it is clear that, once we consider back-scattering (and other) effects which occur as the frequency approaches the plasma frequency of the IPM (typically, about 25 kHz at 1 AU, in the plane of the ecliptic), the situation becomes much more complicated. However, provided the saturated scattering approximation remains valid, we would not expect to see much structure on timescales *less* than the light travel time between the source and the observer.

3. Ulysses Antennas/Receivers

The receivers cover two bands, from 1.25 to 48.5 kHz (lo-band) and from 52 to 940 kHz (hi-band). Hi-band operates in 12 channels, approximately logarithmically spaced, each frequency being determined by one of twelve crystal local oscillators. The intermediate frequency (IF) amplifier frequency is 10.7 MHz, the dynamic range about 70 dB and the bandwidth 3 kHz. Lo-band operates in 64 channels, arithmetically spaced at 0.75 kHz intervals. The IF amplifier frequency is 432.25 kHz, the dynamic range about 70 dB and the bandwidth 750 Hz. The receivers are connected to a 72 m wire antenna perpendicular to the spacecraft spin axis and to a 7.5 m monopole antenna along the spin axis. The spacecraft and the antenna system spin with a 12 s period. The inputs from the antennas can be combined to synthesize an equivalent dipole tilted with respect to the spin axis. By combining the inputs with suitable phase differences the polarization of the incoming waves can be determined (Manning & Fainberg 1980; Stone et al. 1992b). The sensitivity, when used in the separation mode (Stone et al. 1992a), is about $S_{\min} \simeq 5 \times 10^4$ Jy at 100 kHz. In the summation mode the sensitivity is down by about 10 dB.

4. Ulysses URAP Observations

Typical examples of spectra and fixed frequency cuts, relatively close to Jupiter and at distances greater than 5 AU are shown in Figs. 4 through 8. These figures are on a 10 hour time-scale and represent approximately one jovian rotation. Fig. 4 shows the spectra of a bKOM event, recorded in 1991, when Ulysses was approaching Jupiter at a distance of about 1.1 AU from the planet. Lo-band fixed frequency cuts across these same spectra are shown in Fig. 5. The time resolution of both hi- and lo-band data sets is 144 s. Similar plots of a bKOM event, in 1996, are shown in Figs. 6 and 7, recorded when the spacecraft was at a distance of about 7.2 AU from Jupiter. Structuring, which is inherent to the bKOM, can be seen in Figs. 4 and 5 but this is not apparent in Figs. 6 and 7. Presumably most of the structuring has been smoothed out by the effects of temporal broadening over the greater distance travelled by the radiation through the IPM; of course, the intensity at the spacecraft is lower. The difference in structuring is clearly visible in Fig. 8, where 45.5 kHz cuts of the two events shown in Figs. 4 through 7 are compared. In the Fig. 8 plots, three adjacent lo-band frequencies (represented by dotted lines) are averaged. Note that, in Figs. 5, 7 and 8, the intensity scales are not the same for all frequencies.

The reason for averaging three consecutive lo-band frequencies is to remove most of the signal variation due to spinning of the spacecraft-antenna system; three frequencies are collected in six seconds, which is approximately one-half of the

Fig. 4. Typical dynamic spectra of bKOM activity, recorded by URAP on 910928, when Ulysses was approaching Jupiter at a distance of about 1.1 AU.

Fig. 5. Single frequency plots of the event shown in Fig. 4. The unit of intensity is a telemetry unit, approximately proportional to the voltage.

Fig. 6. Dynamic spectra of bKOM activity, recorded by URAP on 960222 when Ulysses was at a distance of about 7.2 AU from Jupiter.

Fig. 7. Single frequency plots of the event shown in Fig. 6. The unit of intensity is a telemetry unit, approximately proportional to the voltage.

spacecraft spin period. In hi-band, the data at a given frequency are collected for 12 s; these data are averaged together and so spin-modulation should not be present in this data. Inbound to Jupiter, close to 1 AU, there was little or no spin-modulation because Jupiter was close to the spin-axis of the spacecraft. Thus, most of the structural features shown in Figs. 4 and 5 are probably intrinsic to the bKOM.

If we assume that the e-folding time and the duration of the main peak of the emission in Fig. 8 (upper section) are the result of temporal broadening of the impulsive bKOM emission, we can assess the effects of interplanetary scattering over the known distance of Jupiter to Ulysses. Detailed examination of URAP data taken during the period January 1, 1995, through July 31, 1996, revealed a number of bKOM events recorded when Ulysses was at distances of about 5 to 7 AU from Jupiter. In some of these, e-folding times could be measured. As the time resolution is 144 s, it can be seen from Fig. 2 that we would not expect to be able to measure temporal broadening on higher frequency URAP channels than 196 kHz.

5. Measurements

The e-folding time of a major emission peak can be measured at different frequencies from single frequency plots, of the type shown in Fig. 8. Sometimes the duration of the activity can also be measured although this is more difficult because of structuring within the bKOM.

The terminology, event, burst and structure, is traditional from the earliest days of Jupiter research. An event may contain a number of bursts (as in Fig. 4) or it may be smoothed to a single burst by scattering (as in Fig. 6). A burst may contain structures (as in Fig. 8, lower section).

The e-folding time was measured from single frequency plots, with the time scale expanded to four hours, using a procedure similar to that of Güdel and Benz (1990). This simply involves measuring the time duration between the time of the peak and the point where the the burst/structure trailing edge profile reaches the -4.3 dB level. Of course, the assumption is made that the decay is approximately exponential.

The problem was to find bKOM bursts or structures that were sufficiently intense, and sufficiently smooth from the peak down to the -4.3 dB level. As might be expected, at distances greater than 5 AU from Jupiter there were not so many bursts and structures observed that were really intense and in the worst cases we had to measure down almost to the background noise level. As we were only trying to measure e-folding times it was decided that the decay of a structure was as valid as the decay of an isolated burst if the structure was of a sufficient intensity and separate down as far as -4.3 dB.

The background levels for the single frequency plots result from a variety of sources, including thermal plasma noise in the vicinity of the antenna, weaker Jovian and solar radio bursts, and, in the higher frequency channels, galactic emission. The variation of the combination of these sources is unpredictable; however, the effect on the determination of e-folding time is only significant for bursts whose peak intensities are within about 5 dB of the background level. The background level is usually different for each event and for each frequency. Furthermore, the thermal plasma noise varies with the *in situ* electron density and temperature and, consequently, can cause significant changes in the background level on short time scales.

Fig. 8. Comparison of single frequency plots from the events shown in Figs. 4-7. Each 45.5 kHz plot is the average of three adjacent frequencies represented by dotted lines. The dB unit of intensity is proportional to the emitted power.

Fig. 9. e-folding time against frequency for 1991 bKOM events. The straight line represents the 8.3 min limit predicted for observations close to 1 AU from the planet.

Fig. 10. e-folding time against frequency for 1995/6 bKOM events. The straight line represents the 8.3 min AU^{-1} limit drawn for 6.6 AU, about 55 min, for observations at 5.5 to 7.2 AU from Jupiter.

Fig. 11. Average e-folding time at 40.25 to 47.75 kHz against Jupiter distance. The straight line represents the 8.3 min AU^{-1} relationship predicted for observations at the lowest frequencies.

Fig. 12. Average e-folding duration at 40.25 to 47.75 kHz against Jupiter distance.

Fig. 13. Average e-folding time at 40.25 to 47.75 kHz against SWOOPS electron density at the spacecraft. Points shown as $+$ are for measurements made when Ulysses was close to the plane of the ecliptic. Points shown as $*$ are for measurements made when Ulysses was at heliocentric latitudes greater than 50°.

Fig. 14. Average e-folding times of bKOM events, observed in 1991 at 40.25 to 47.75 kHz, over-plotted on a time-series of SWOOPS electron density measurements at the spacecraft.

Thus the main uncertainty when measuring low intensity emission was in establishing where the background level was and whether or not we were justified in using that particular burst/structure at all. This was achieved by trial and error adjustment of the colour scale on the spectra, to give the best definition of the event, and by trying to infer the background level from the single frequency plots, often over a longer period of time than four hours.

Evidently, the error varies with the intensity of the burst and, therefore, with the distance from Jupiter. In the case of the weakest bursts, the error is probably dominated by the proximity to (variable) background. It is estimated that the maximum uncertainty in the e-folding measurements is about $\pm 25\%$ but more typically about $\pm 15\%$.

In the case of more intense bursts, the uncertainties are the result of deviations from e-folding, residual spin modulation, and noise fluctuations in the system. These, of course, also exist for the weak bursts; however, they represent only a small part of the total uncertainties. For the more intense bursts, we estimate that the uncertainties in the e-folding measurement are less than $\pm 10\%$.

Main peaks of activity often have ragged edges, even when observed at distances greater than 5 AU, and we might well ask, are these the remnants of some characteristic of the bKOM or, in the lo-band data, are they the remnants of spin-modulation? This problem is overcome to some extent in lo-band, as described in the previous section, by plotting the average of three adjacent frequencies, as shown in Fig. 8, rather than an individual frequency. Some, but not all, of the ragged edges are smoothed out and possible effects of the spinning spacecraft and antenna are reduced. We have seen that this is not necessary in hi-band.

The e-folding times are plotted against frequency in Figs. 9 and 10. In Fig. 9, the straight line represents the limiting value of 8.3 min, mentioned in Section 2, for the temporal broadening observed at about 1 AU from Jupiter. In Fig. 10, the line is drawn for 6.6 AU, about 55 min, for observations at 5.5 to 7.2 AU from Jupiter. The corresponding solar distances are shown on both figures.

It is interesting to see how the e-folding times vary with distance of the spacecraft from Jupiter; this is demonstrated in Fig. 11, where measurements of the e-folding times, at several different lo-band frequencies between 40.25 and 47.75 kHz, are averaged for each event and plotted against the distance of Jupiter from the spacecraft. It can be seen that the e-folding time increases with distance, commensurate with the limiting value of about 8.3 min AU^{-1}, mentioned in Section 2, and represented by the straight line. In this plot, bKOM events recorded at intermediate distances of about 2.5 to 3.6 AU have been added to the data shown in Figs. 9 and 10. The average structure durations, measured at 4.3 dB down from the peak, are plotted in Fig. 12.

6. Electron density measurements

The SWOOPS experiment on board Ulysses (Bame et al. 1992; Phillips et al. 1995) measured electron density in the vicinity of the spacecraft. Provided that the spacecraft is on the Jupiter side of the Sun and not too far from the Sun-Jupiter line, the inverse square density gradient in the IPM will usually mean that it is this local material that dominates in the scattering process. The bKOM is known to be beamed quite sharply (Leblanc 1988) and so the electron density at the spacecraft will be an indication of the close-to-observer density in the direction of Jupiter.

In Fig. 13, the average e-folding times (from Fig. 11) are plotted against the hourly-average electron density measurement closest to the time of the bKOM event. These values represent the total electron density at the spacecraft (assumed to be equal to the positive charge density = $n_{\rm p} + 2n_{\rm He}$ as the electron data is noisier than the proton data). Measurements made at high and low heliocentric latitudes are distinguished.

In Fig. 14, bKOM events recorded during the period DOY 91001 through 91150, when Ulysses was travelling close to the plane of the ecliptic, are over-plotted on a time series of electron densities measured at the spacecraft by the SWOOPS experiment. The corresponding average e-folding times are represented by the height of each point above the x-axis. Thus an electron density peak a little to the left of a bKOM event would have been measured at Ulysses before the radio emission was received and may be a rough indication of a density enhancement somewhere close to the spacecraft and in the direction of Jupiter at the time when the event was received.

All of the 1995/96 bKOM events were recorded when Ulysses was out of the plane of the ecliptic and so the electron densities and corresponding plasma frequencies would be expected generally to be lower than those characteristic of measurements made in the plane of the ecliptic. For example, in the events of 950102 and 950707, the plasma frequencies were about 9 kHz and 8 kHz when the spacecraft was about 1.55 and 1.85 AU from the Sun and at heliocentric latitudes of $-50.4°$ and $70.5°$, respectively. The corresponding jovicentric latitudes were about $-15.4°$ and $14.5°$ at distances of about 5.55 and 5.89 AU, respectively, from Jupiter.

7. Discussion

Several points of interest arise out of the foregoing, as follows:

1. In Fig. 9, almost all of the e-folding times measured at distances of about 1 AU from the planet are significantly shorter than 8.3 min and mostly below about 5 min, even at the lowest frequencies. This suggests that the temporal broadening does not reach its limiting value at 1 AU from Jupiter and that the observations here show intrinsic characteristics of the bKOM. We would expect this, as the scattering angles are relatively small so far from the Sun, even at ~ 40 kHz.
2. In Fig. 10, the e-folding time values close to 45 kHz range from about 14 to 80 min, all but two of which are below the 8.3 min AU^{-1} line drawn here for 6.6 AU, about 55 min.

At 80 to 120 kHz, the e-folding times are well below this limit. We regard this as confirmation of the limit to temporal broadening predicted in Section 2. The scaling factors for the 4.4 and the 4.0 laws are obviously invalid here being defined for observations 1 AU from the Sun.

3. Fig. 11 demonstrates clearly that the e-folding time and hence the temporal broadening increases with distance from Jupiter at $\sim$ 45 kHz. Most of the values lie close to but just below a line representing 8.3 min AU^{-1}, consistent with the light travel time from the source to the observer, assuming that the scattering is more or less isotropic at frequencies close to about 45 kHz.
4. Durations are more difficult to measure than e-folding times, due to structuring within the event. Nevertheless, in Fig. 12 the available measurements of the corresponding average durations show a similar trend to that shown by the average e-folding times in Fig. 11.
5. The electron densities measured at the spacecraft, shown in Fig. 13 and show little correlation with the measured e-folding times. As Δn_{e} has been taken to be proportional to n_{e}, it follows from Eqns (1) and (2) that $\tau_{\mathrm{b}} \propto \theta_{\mathrm{s}}^2 \propto n_{\mathrm{e}}^2$ at a given frequency, where n_{e}^2 is taken as a suitable average along the line-of-sight. There are two reasons why we might not expect a strong correlation between the in situ density measurement and the e-folding time. Firstly, the path-lengths are long compared with typical compression and rarefaction zones within the IPM, so that a point measurement at the spacecraft cannot be expected to accurately reflect the line-of-sight electron density to the source. Secondly, if the scattering process has truly reached saturation then variations in plasma density will have little effect on temporal broadening unless the density drops below the saturation level.

   The measurements made when Ulysses was at high heliocentric latitude ($\geq 50°$) seem to suggest that e-folding times are greater when the electron density is lower. There are two considerations here, however. Certainly, electron densities measured out of the plane of the ecliptic will be lower but all of the high latitude measurements shown here were made in 1995/6 when Ulysses was at distances of 5.5 to 7.2 AU from Jupiter and, as we have seen in Fig. 11, the measured values of e-folding time increase with distance from the planet anyway.

   The measurements shown in Fig. 14 were all made close to the plane of the ecliptic but again there is no obvious indication of any influence of the electron density on the e-folding times. A few events occur close to minima in the electron density time series but others do not and, of course, as the bKOM is an intermittent radiation, there is no way of telling if an electron density enhancement has actually prevented the passage of the emission.
6. There are indications (Figs. 3a and 3b) that temporal broadening should impose a steeper leading edge than trailing edge on a structure, similar in fact to any unresolved radio burst. Most of the fixed frequency plots used for measuring structure duration show little or no indication of this assymetry, however. It is possible that, even at distances greater than 5 AU, we may still be seeing intrinsic bKOM structural characteristics as well as temporal broadening in the IPM although the data shown in Figs. 9 and 10 hardly supports this. It seems more likely that at hi-band kHz frequencies, above 52 kHz, the assymetry may not be detectable with the time resolution of 144 s, mentioned in Section 4, while at lo-band frequencies, close to 47 kHz, the longer trailing edge may be obscured by the background.
7. As described earlier, the URAP instrument was designed to determine the direction of a radio source, using the 'spinning spacecraft technique' (Manning & Fainberg 1980). Fitting the spin modulation imposed on the signal by the rotation of the spacecraft yields the direction of the source, its angular size, and, in some modes of the URAP instrument, the full polarization. For selected bKOM events in 1995 at ($\sim$45 kHz), this fitting yields a half-angle for the source size kHz of approximately 60° (for a uniform circular source). The intensity distribution of the scattered waves is certainly not a uniform circular distribution but, on the other hand, one cannot map the distribution with a single short dipole system. A half-angle of the order 60° is consistent with the temporal broadening reported above, i.e., 8.3 min AU^{-1}. Inbound to Jupiter in 1991, the spin axis of Ulysses pointed towards Jupiter, causing the spin modulation to be very shallow. This small modulation combined with the burstiness of the bKOM causes the fitted parameters to be poorly-determined. Also, it appears that the smaller distance to Jupiter and the corresponding shorter durations of bursty structures, as determined above, further hinder the fitting. In other words, the 12 s spin period of Ulysses is not ideal for fitting spin modulation of bursty Jovian sources. Consequently, further work will be required for the detailed presentation of scattering as measured by the angular size of the bKOM emission.

8. Conclusion

We have used observations of the jovian bKOM emission, from the URAP experiment on board Ulysses, to study scattering effects in the IPM and to impose some constraints upon models of the scattering medium. Observations of the bKOM at distances of about 1 AU from Jupiter, when scattering effects are negligible, are assumed to show the intrinsic temporal characteristics of the emission and these have been compared with observations made at distances of 5.5 to 7.2 AU.

1. The bKOM appears to be considerably less structured when observed at distances greater than about 5 AU from Jupiter as compared to observations at distances of about 1 AU.
2. Measured values of the temporal broadening are found to increase with decreasing frequency, reaching a limiting value roughly equal to the light travel time from source to observer when the scattering fills most of the sky. In particular, the e-folding times measured close to 45 kHz lie close to but just below a line representing 8.3 min AU^{-1} (Fig. 11), consistent with this interpretation.

3. The absence of asymmetry in the bKOM structures may be an effect of the limited temporal resolution available.
4. Electron density measurements at Ulysses do not show any obvious influence on the measured e-folding times, probably reflecting the highly variable density along the line of sight to Jupiter.

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