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# Pick-up ions and associated wave energy transport at Comet P/Halley: A case study

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**Abstract.** During the flyby of the spacecraft Giotto at comet p/Halley Poynting vectors and Elsässer variables have been determined to study wave propagation directions. The observed wave properties are compared with the theoretically predicted $RH^-$, $LH^+$ and $LH^-$ wave modes. Between 10:36 and 19:11 SCET on March 13, 1986 the predicted dominating energy propagation direction mostly corresponds with the observed one. Only between 12:11 and 13:44 SCET there is no agreement. In this region the excitation of waves is dominated by pick-up ions which are not locally implanted ions in the solar wind but have been picked-up outside the plasma regime studied, and whose free energy is not already used up.

## Introduction

The main interaction between a comet and the solar wind is due to mass loading of the solar wind by cometary ions. In the solar wind frame the newborn cometary ions are at the local point of pick-up, implanted in the solar wind and interact resonantly with the generated plasma waves. The mechanism involved is the Doppler-shifted ion cyclotron resonance.

Due to the scattering of the ions toward a bispherical distribution in the velocity space they lose energy in the solar wind frame, which is available to the wave spectrum. A comparison indicates that the free energy is not immediately released as wave energy. Pick-up and isotropization is thus not an instantaneous process [*Huddleston and Johnstone*, 1992].

*Thorne and Tsurutani* [1987] have provided a description of wave generation processes based on local pick-up conditions. In the present paper we shall compare theoretical predictions with energy flow considerations from analysis of magnetic field and plasma observations in the upstream region of comet p/Halley.

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## Observations and theory

From the instability condition for the ion cyclotron resonance together with the wave phase velocity $u_{\|} = \omega/k_{\|}$ one obtains for the ring beam unstable waves [*Thorne and Tsurutani*, 1987]

$$v_{res} = u_{\|}\left(1 + n\frac{\Omega_i}{\omega}\right) \tag{1}$$

with $v_{res}$ the magnetic field aligned particle velocity in the plasma frame, $k_{\|}$ the wave vector along the magnetic field $\vec{B}$, $\omega$ the positive wave frequency and $\Omega_i$ the gyrofrequency of the ions. $n = 0, \pm1, \pm2, ...$ is a multiplier of gyrofrequency. Only first order resonances need be considered. $n = +1$ describes right-hand polarized waves ($RH$ mode) and $n = -1$ left-hand polarized waves ($LH$ mode). If the cometary pick-up ions move in the solar wind frame back towards the Sun with velocity $v_{\|}^{+} \simeq v_{sw} \cdot \cos\alpha$ together with a two component cold plasma model one obtain resonance conditions depending on the angle $\alpha = \cos^{-1}\left|(\vec{v}_{sw} \cdot \vec{B})/(v_{sw} \cdot B)\right|$ between $\vec{B}$ and the solar wind velocity $\vec{v}_{sw}$ and on the field aligned Alfvén-Mach number $M_{Ar} = v_{sw} \cdot \cos\alpha / v_A$. The generation depends also on the observed heavy ion mass ($m_+ = 18$) and on the relative number density of heavy ions ($\eta_+ \simeq 10^{-2}$). The following modes are possible: One $RH^-$ mode directed towards the Sun and two $LH$ modes, one towards ($LH^-$) and one away from the Sun ($LH^+$) [*Thorne and Tsurutani*, 1987].

In the cometary environment the conditions of theoretically predicted wave modes are as follows [e.g. *Neubauer et al.*, 1993]: for $M_{Ar} > 1.25$ there is the $RH^-$ mode, always dominating for $30° \leq \alpha \leq 75°$; for $M_{Ar} < 0.6$ the $LH^-$ mode will be excited; the $LH^+$ mode exists for any $M_{Ar}$. Its wave growth rate is larger than that of the $LH^-$ mode, if both are excited, and larger than that of the $RH^-$ mode, if $\alpha \geq 75°$.

To determine the wave energy transport from actual observations the concept of Elsässer variables

$$\delta\vec{Z}^{\pm} = \delta\vec{v} \mp \delta\vec{v}_A$$

is used [*Tu et al.*, 1989] where $\delta\vec{v}$ and $\delta\vec{v}_A$ are the fluctuations of the solar wind and Alfvènic velocity. The energy density of the two possible Alfvénic wave modes propagating in opposite directions is defined as *Marsch and Mangeney* [1987]

$$E^{\pm} = \frac{1}{2}\delta\vec{Z}^{\pm} \cdot \delta\vec{Z}^{\pm}$$

That is, if the ambient magnetic field $\vec{B}$ is directed outward from the Sun, $E^{+}$ describes the energy density of waves travelling away and $E^{-}$ of waves travelling towards the Sun.

Another way to determine the direction of the wave energy flux, is via the Poynting vector $\vec{S}$, defined by

$$\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{b}$$

where $\vec{E}$ is the fluctuating electric field vector and $\vec{b}$ the disturbance vector of the magnetic field $\vec{B}$. If the background magnetic field $\vec{B}_0$ is parallel to the $z$-component of a field aligned system and the frozen-in theorem is valid, the Poynting flux of Alfvén waves is along the ambient magnetic field $\vec{B}$. Previous studies revealed that fluctuations in the solar wind as well as in the upstream region of comet p/Halley are predominantly Alfvénic fluctuations [*Bavassano and Bruno*, 1989; *Glassmeier et al.*, 1989].

In our analysis we use data from the magnetometer and Johnstone plasma analyser instruments on board of Giotto. The data used have a temporal resolution of 8 s. The data are from the inbound leg upstream from the bow shock, between 10:36 and 19:11 SCET (Space Craft Event Time) on March 13, 1986. This corresponds to spacecraft distances from the nucleus of $\sim 3.3$ to $1.2 \cdot 10^6$ km. To calculate the specific energy densities $E^{\pm}$ and the Poynting flux $\vec{S}$, we use smoothed cross spectral density estimates, performed on 512 sample points. The time of each cross spectral density estimates is the mid time for each data subset and the subsets overlap each other half. To ensure that the sense of propagation of $E^{\pm}$ with respect to the Sun does not change depending on the mean magnetic field direction, we use $-\vec{B}$ instead of $\vec{B}$ if the radial component of $\vec{B}_0$ is positive in HSE system.

Fig. 1 displays the magnitude of the magnetic field $B$, the angle $\alpha$, the parallel Mach number $M_{Ar}$ and sign of $\vec{B} \cdot \vec{v}_{sw}$. If $\mathrm{sign}(\vec{B} \cdot \vec{v}_{sw}) = +1$ the direction of the magnetic field is away from the Sun and vice versa for $\mathrm{sign}(\vec{B} \cdot \vec{v}_{sw}) = -1$. To calculate the relative number density of heavy water group ions $\eta_{H_2O}$, we used the model of *Huddleston et al.* [1990] to determine the water group ion density along the inbound path. Another panel indicates the presence of the theoretically predicted $RH^-$, $LH^+$ and $LH^-$ wave modes by presence of arrows. Arrows pointing from left to right are parallel and arrows from right to left are antiparallel to $\vec{B}_0$. *Neubauer et al.* [1993] have made similar examinations at comet P/Grigg-Skjellerup. The bolder arrows have the largest wave growth rate, so this wave mode is expected to be dominating. Fig. 1 also displays the specific energy densities $E^{\pm}$ and the $z$-component of

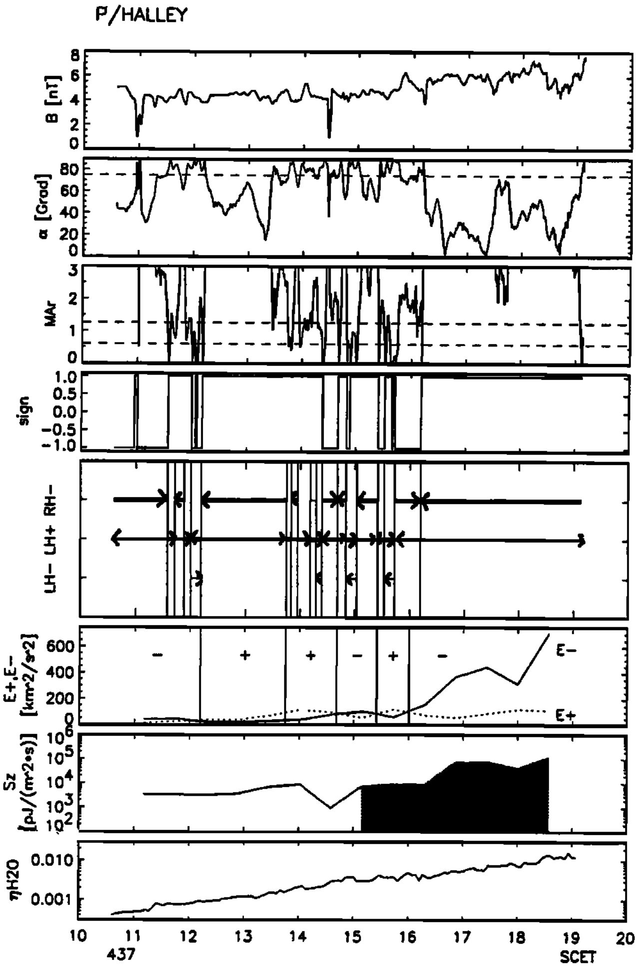


**Figure 1.** Shown are the magnetic field magnitude $B$, the angle $\alpha$, the Mach number $M_{Ar}$, the sign of $\vec{B} \cdot \vec{v}_{sw}$ and the relative number density of the heavy water group ions $\eta_{H_2O}$ as a function of time. One panel shows the presence of theoretically predicted $RH^-$, $LH^+$ and $LH^-$ waves by presence of arrows. In the sixth panel are the specific energy densities $E^{\pm}$ shown. In fact of the observation expected wave modes are signed by + and −. Another panel shows the Alfvénic part of the Poynting flux in a field aligned system. For further explanations, see text.

the Poynting flux $S_z$ for the frequency range 3-60 mHz. This range is used because the cometary influence on wave properties is dominant for frequencies above the gyrofrequency of the water group ions (~3 mHz).

Theoretically the $RH^-$ mode should be dominating during the time intervals 10:36-11:34, 11:42-11:52, 12:11-13:44, 13:50-13:57, 14: 24 -14:50, 15:02-15:25, and 15:43-19:11 SCET. At all other time intervals the $LH^+$ mode is theoretically dominating. The $LH^-$ mode is only excited in four short time intervals, but it is never dominating.

These expectations may be compared with the observed specific energy densities. Until ~16:00 SCET $E^+$ and $E^-$ are of the same of magnitude. Later $E^-$ increases and $E^+$ stays at the same level. In the case $E^+ > E^-$ one expects wave propagation away from the

Sun dominating. This is marked in the sixth panel with a "+". The case $E^- > E^+$ is vice versa. The "−" mode is observed between 10:36 and 12:11, 14:41 and 15:25, and 16:00 and 19:11 SCET; and the "+" mode is observed during the intervals 12:11-14:41 and 15:25-16:00 SCET.

The observed "−" modes agree with the theoretically predicted dominating $RH^-$ modes. The "+" mode between 15:25 and 16:00 SCET agrees also with the predicted dominating $LH^+$ mode as well as between 13:44 and 14:41 SCET. But between 12:11 and 13:44 SCET the observed "+" mode does not agree with the predicted dominating $RH^-$ mode. The observed main propagation direction is away and the predicted one is towards the Sun.

To compare the propagation direction with respect to the ambient magnetic field $\vec{B}_0$, the $z$-component of the Poynting flux is shown in a field aligned system. The shaded region describes in Fig. 1 an energy flux antiparallel to $\vec{B}_0$ and the light one parallel energy flux. Between the last light value (14:35 SCET) and the first dark value (15:09 SCET) the direction of the Poynting flux reverses. Until ~14:45 SCET the energy flux is parallel to $\vec{B}_0$ and afterwards antiparallel. In the time intervals 10:36-12:11 and 13:44-14:41 SCET the observed propagation parallel to $\vec{B}_0$ agrees with the theoretically predicted propagation direction (see Fig. 1). After 14:45 SCET the observed antiparallel propagation agrees mostly with the arrows of the dominating mode from right to left, while between 12:11 and 13:44 SCET the observed parallel propagation does not agree with the predicted antiparallel propagation, much as inferred from the Elsässer variable analysis.

## The 12:11 – 13:44 SCET event

Between 12:11 and 13:44 SCET, that is at distances of ~2.9 to $2.5 \cdot 10^6$ km, no agreement is found. In this region the observations and theory predicted mode would agree, if the theoretically dominating mode would be the $LH^+$ mode rather than the $RH^-$ mode.

A closer look at the observations in this region shows a clearly visible wave event between 12:20 and 12:54 SCET. The period of the event, ~ 200 s, is with the water group ion gyroperiod [*Acuna et al.*, 1986]. A minimum variance analysis and a wave mode analysis indicates in addition that the propagation is almost parallel to $\vec{B}$ [*Glassmeier et al.*, 1995] and points away from the Sun. However, the characteristics of this particular wave event agree with those resulting from the Elsässer variable and Poynting flux analysis.

The theoretical predictions are based on the assumption that locally conditions of wave excitation are representative for the excited waves observed at that point. This implies that local values of $\alpha$ and $M_{Ar}$ have been used to predict wave characteristics. As discussed by *Coates et al.* [1989] pitch angle isotropization times are of the order of several hours. Thus, we have to question our assumption of local plasma properties dominating local wave properties at all. It might well happen that plasma properties away from the local observation point have a major influence on wave characteristics. Two basically different situations are possible. First, local wave properties are due to waves which have been propagated from outside into the plasma regime studied. Second, wave properties are due to a local instability with the unstable pick-up ion distribution dominated by ions picked-up far away from the studied plasma regime and the locally picked-up ions playing a minor role only. This implies that the local pick-up conditions as used in Fig. 1 are not those determining local wave characteristics.

The first of these possibilities we do not consider any further due to a lack of suitable observations. However, if the non local plasma properties determine the local wave properties, one must examine the change of the angle $\alpha$ between the non local point of pick-up and the local studied point. Therefore, several possibilities to explain the excitation of the observed $LH^+$ mode are given depending on the order of the change of $\alpha$.

Between 12:11 and 13:44 SCET $\alpha$ is mainly between 10° and 60°, and according to the theory of *Thorne and Tsurutani* [1987] $RH^-$ waves are expected. Before and afterwards, $\alpha$ is larger than 75°, thus a ring-type distribution and $LH^+$ waves are expected, much as observed. In Fig. 2 the water group ion phase density in the solar wind frame at 12:30 SCET is shown [*Coates et al.*, 1989]. The injection point, indicated by a star, is located at $\alpha \simeq 45°$, but the measured water group ion phase space densities are observed for $65° \leq \alpha \leq 90°$. Although the expected distribution is a beam, a ring distribution is observed. *Coates et al.* [1989] indicate that at distances to the nucleus larger than $2.5 \cdot 10^6$ km pitch angle scattering is weak.

That implies that the pick-up ion distribution seen at a given point is the result of cometary ions picked up under conditions different than the local one. In our particular case solar wind conditions before 12:11 SCET governed the pick-up ion distribution. The older pick-up ions are implanted at a angle $\alpha$ larger than lo-

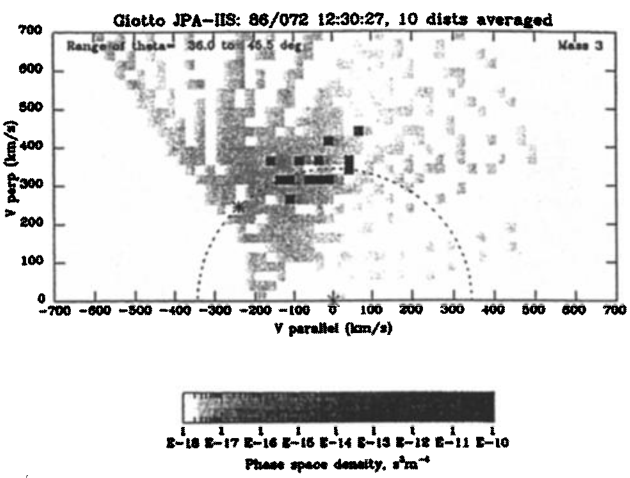


**Figure 2.** The water group ion phase space density plot in the solar wind frame at 12:30 SCET averaged over 21 min 20 sec. The range of theta given in the plot is the range of $\alpha$ during this interval. The average value is shown by the star ( figure courtesy from *A. J. Coates*).

cally observed. With $\alpha \geq 75°$ like in the region before 12:11 SCET, the theoretically predicted dominating wave mode is the $LH^+$ mode, as observed. This result may be used to derive information about the pitch angle isotropization time $\tau_p$, too. If $\tau_p \approx 0$, local plasma properties would govern wave characteristics, while $\tau_p \gg 0$ would result in temporal variations with time scales $\tau < \tau_p$ causing inconsistencies between observed and locally predicted characteristics. From this we infer pitch angle isotropization times of the order of hours, much as suggested by the analysis of *Coates et al.* [1989].

An alternative explanation may be the following: The wave energy in a plasma parcel observed by Giotto is composed of wave energy due to the action of pick-up instabilities and the initial wave energy carried in the undisturbed solar wind far upstream of comet Halley. This initial wave energy is large for $E^+$ and small for $E^-$, because the solar wind is dominated by outward propagating Alfvén waves. Thus the portion of the wave energy $E^+$ due to pick-up instability action can be obtained by shifting $E^+$ downwards by a constant value and leaving $E^-$ as it is. One can then see that the discrepancy more or less disappears. Unfortunately, the original wave energy of the solar wind origin cannot be determined very precisely.

## Discussion and Summary

The inbound leg upstream of the bow shock of comet p/Halley has been investigated with respect to wave energy transport. The investigated region can be subdivided into several regions. Until ~16:00 SCET waves with comparable energy densities are propagating in opposite directions, that is towards as well as away from the Sun. Later energy density of the wave mode propagating towards the Sun increases strongly.

These observed wave energy transport directions are compared with the theoretically predicted $RH^-$, $LH^+$ and $LH^-$ wave mode owing to the ion cyclotron resonance instability. In general we found sufficient agreement between observed and predicted energy flow direction and conclude that $RH^-$ waves have been driven unstable by pick-up ion instability. Only between 12:11 and 13:44 SCET a clear discrepancy is found. In this interval we conclude the $LH^+$ mode being the most unstable one with the driving ion distribution having been generated under pick-up conditions different from the local ones.

These older pick-up ions are implanted into the solar wind under a different constellation of the magnetic field with respect to the solar wind velocity than in surrounding regions. Because of the frozen-in theorem the reason for this is probably a temporal propagating not convecting variation of the magnetic field direction. We conclude that quasi-linear theories must be treated with care, if temporal variations of pick-up conditions are not taken into account.

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