OBSERVATIONS OF THE PLASMA FLOW IN COMET P/SWIFT-TUTTLE

Michael E. Brown, Christopher M. Johns, and Hyron Spinrad

Department of Astronomy, University of California at Berkeley

Abstract. We present direct ground-based observations of the plasma flow sunward and tailward of the nucleus of comet P/Swift-Tuttle. The observations are long-slit high resolution spectra of the H₂O⁺ emission centered at 6199Å with a velocity resolution of about 7 km s⁻¹ (FWHM) and a spatial resolution of about 10⁴ km at the comet. Emission is visible from just inside the predicted position of the cometopause on the sunward side of the nucleus out to 5 × 10⁴ km on the tailward side. The deceleration of the solar plasma on the sunward side is clearly observed as is the acceleration of cometary ions into the tail. These observations show the effectiveness of ground-based methods for the systematic study of cometary plasmas and point to the need for a better theoretical understanding of their acceleration mechanisms.

Introduction

Our understanding of cometary plasmas was greatly increased by the knowledge gained from the in situ measurements obtained by the spacecraft arms to comets Halley and Giacobini-Zinner. But while spacecraft provide a wealth of information, the information is usually limited to a snap shot of a single object at a single instant. Use of ground-based observation allows the long term study of individual comets and the systematic study of the entire class, but ground-based measurements of plasma properties in comets have traditionally been difficult and have not been detailed enough to allow the study of important physical regimes. For three decades, the plasma velocities in the tails of comets have been studied from the ground through direct observations of the proper motions of features in the tails. For example, Jockers [1981] compared sequential images of comet Kohoutek and measured the motions of coherent features which he could discern in multiple images. This method is difficult because the velocity can only be measured at locations along the tail where these features are visible, and the mechanism producing the features may also affect the plasma flow. Direct Doppler measurement of the tail velocities was first achieved by Huppler et al. [1975] for comet Kohoutek and was systematically used for the study of plasma velocities in comet Halley by Scherb et al. [1990]. These Doppler measurements used a high-resolution scanning Fabry-Perot spectrometer to isolate the 6199Å H₂O⁺ emission and to detect the small velocity shifts in the emission. To date, the use of this Fabry-Perot method has required a large entrance aperture to gather sufficient light, so use of this method has not allowed the study of small-scale structure. The method of short-slit spectroscopy was also used for comet Halley [S. Wyckoff and E. Lindholm, private communication, 1993], but here the aperture is too small to allow the measurement of the plasma parameters in more than one small region at a time, so again anything other than the gross structure remains unresolved.

We present here results from the first ground-based observations with sufficient velocity and spatial resolution to allow continuous measurement of velocity structures over a wide range of spatial scales. In the next section we describe the observational method and the details of the data reduction. The following section discusses the implications of the plasma velocity measurements, and we conclude with a few thoughts on strategies for future observations and a comment on the need for a different type of theoretical understanding.

Observations

The observations of plasma velocities in comet P/Swift-Tuttle were made using the 0.6 meter condé auxiliary telescope coupled to the Hamilton echelle spectrograph at Lick Observatory between the nights of 23 November and 24 December 1992. To obtain both spectral and spatial information we used the method of long-slit spectroscopy which gave a spectrum at each position along the slit. The spectra were recorded by a Ford 2048 X 2048 CCD chip that was binned by a factor of four in the spatial dimension and a factor of two in the wavelength dimension to decrease the readout noise of the chip. The nucleus of the comet was placed near one edge of the slit, and the slit was then aligned along the tailward projection of the sun-comet vector. The observations achieved a spectral resolution of λ/Δλ(FWHM) ~ 40000 (corresponding to a velocity resolution of about 7 km s⁻¹) and a spatial resolution of about 10 arc seconds per binned pixel (at typical comet geocentric distances of about 1.3 AU, 10 arc seconds projected to about 10⁴ km) along a 6 arc minute slit (about 4 × 10⁴ km). Exposure times were between 1800 and 3600 minutes, and the comet had an approximate observed visual magnitude of 5.0 during the period of observations. The heliocentric distance of the comet ranged from 1.01 to 0.98 AU.

The raw two-dimensional spectra were reduced identically: first, the bias and dark currents were subtracted, and then the spectra were flat-fielded using the sky spectrum. The wavelength scale for the spectra was also calibrated from spectra of a thorium-argon lamp with a high density of known spectral lines. The wavelength scale of each spectrum was then shifted to account for the earth-comet velocity, which was between 21 and 28 km s⁻¹, by placing the H₂O⁺ emission lines of the nucleus at the known H₂O⁺ rest emission wavelength. Figure 1 shows the two-dimensional spectrum from the...
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the cosine of the sun-comet-earth angle to determine the
sun-comet vector we divided the measured velocity by
of the sky. To correct the velocity to that along the
plane of the sky, we multiply the measured velocity by
the sine of this angle because of the quasi-cylindrical geometry and central
location in the real spectrum. Because of the high
signal-to-noise of these observations, this cross-correlation
method allowed determination of relative velocities to a
one sigma accuracy of better than 1 km s\(^{-1}\).

Although these observations represent a column
integration through the coma rather than a single
measurement along the sun-comet line, we believe that
because of the quasi-cylindrical geometry and central
brightness concentration of the emission, the column
integrated velocity is typical of the velocity in the plane
of the sky. To correct the velocity to that along the
sun-comet vector we divided the measured velocity by
the cosine of the sun-comet-earth angle to determine the
component along this vector. Similarly, we divided the
distance along the plane of the sky by the sine of this angle
to determine the distance along this vector. Figure 3
shows the results of the measurements of the velocity
shifts for the six best spectra and lists the time of center
exposure for each spectrum.

As neutral water molecules sublimate from the
cometary nucleus and flow outward, they eventually
ionize into \(\text{H}_2\text{O}^+\) or dissociate into smaller fragments
which may themselves become ionized. The newly
created ions are picked up by the solar wind flow and
quickly accelerated to the local solar wind velocity. Thus
measurements of the cometary plasma flow are equivalent
to measurements of the solar wind plasma flow at that
location in the comet. When encountering a comet, the
solar wind flow goes through three boundaries on the
sunward side of the comet: the bow shock, the
cometopause, and the ionopause [Flammer 1991]. Outside
of the cometary bow shock the solar wind flows mostly
undisturbed, at a typical velocity of about 400 km s\(^{-1}\).

As the density of neutrals continues to increase,
the solar wind (now heavily contaminated with cometary
pick-up ions) eventually reaches the ionopause where
strong collisional coupling between cometary neutrals and
ions completely excludes the solar wind plasma.

Flammer [1991] has estimated the locations of these
boundaries for Halley-type comets. Preliminary obser-
vations indicate that Swift-Tuttle had a production rate
almost comparable to that of Halley at the 1986 encoun-
ters [A'Hearn 1992], thus we will consider the Halley
estimates approximately appropriate for comet P/Swift-
Tuttle. The estimates predict the bow shock around
5 \times 10^5 km, the cometopause around 5 \times 10^4 km, and
the ionopause around 4000 km.

Figure 3 shows the measured plasma velocities on
the sunward side of the nucleus. All detections of
cometary ions are inside of the predicted location of the
bow shock and also inside of the predicted location of the
cometopause. With the modest spatial resolution
achieved, however, the region of the ionopause remains
unresolved. As expected from the basic scenario outlined

Fig. 1. A long slit \(\text{H}_2\text{O}^+\) spectrum of Comet Swift-Tuttle
from the night of 30 November 1992. The emission from \(\text{H}_2\text{O}^+\) is
clearly visible as the four slanted emission lines; the slant
of the lines is caused by the doppler shifts that is it our
goal to measure. The continuous emission at the nucleus
is caused by sun light scattered from the dust coma of
the comet. Figure 2 compares the spectra at three points
along the tail of the comet and shows the excellent signal-
to-noise achieved in these observations.

To obtain precise velocity measurements from the
spectra we used a cross-correlation method where the
spectrum at each spatial location is cross-correlated with
the spectrum at each other location to obtain the velocity
shift. From this system of mutual cross-correlations
we obtained a best-fit for the velocity shift at each
spatial location. For each spectrum, we determined the
value of the orbit by using the same cross-correlation
method on a hundred simulated two-dimensional spectra
having the same velocity shift and random noise at a
level determined by the measured signal-to-noise at each
location in the real spectrum. Because of the high
signal-to-noise of these observations, this cross-correlation
method allowed determination of relative velocities to a
one sigma accuracy of better than 1 km s\(^{-1}\).

Although these observations represent a column
integration through the coma rather than a single
measurement along the sun-comet line, we believe that
because of the quasi-cylindrical geometry and central
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distance along the plane of the sky by the sine of this angle
to determine the distance along this vector. Figure 3
shows the results of the measurements of the velocity
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exposure for each spectrum.

Fig. 2. One dimensional spectra at four distances from
the nucleus. The velocity shift of the spectra is clearly
visible in these plots, as is the high signal-to-noise of these
observations. The plasma temperature can be measured
from the line width of these emissions.
The details of the near-nuclear plasma flow in the tailward directions of comets are not as well understood as those of the flow on the sunward side. Although much information was gained about the more distant tail regions by the ICE spacecraft encounter with comet Giacobini-Zinner, the tail side of the ionopause and near-nuclear regions was not encountered by any spacecraft.

MHD simulations have yet to reach a self-consistent solution for this region [Neubauer 1991], and no previous ground-based observation has had sufficient velocity and spatial resolution to discern this region. Our high resolution long-slit spectra provide the first contiguous and detailed look at this region of a comet.

Examination of the near-nuclear velocities on the tailward side of the nucleus in figure 3 shows a smooth transition from the low velocity flow near the cometary nucleus into the tail region. In each spectrum the tailward acceleration starts at the first measured point past the nucleus, thus the tailward extent of the low velocity ionosphere is restricted to a distance of less than about \(10^4\) km. The MHD models of Schmidt and Wegmann [1991] predict a teardrop shape to the ionopause, with the tailward section extending to around \(2 \times 10^4\) km. Because of the stretching on the tailward side we do have sufficient spatial resolution to view into this region of the ionopause, and though our observations are a column integration through the comet and the view is perhaps distorted by plasma flow on the outside of the ionopause, our observations indicate a smaller tailward ionopause than currently predicted. In addition, at a distance of about \(5 \times 10^4\) km, where we measure velocities of around \(5 \text{ km s}^{-1}\), the numerical models [e.g., Schmidt and Wegmann 1991] predict much higher velocities of around \(15 \text{ km s}^{-1}\). This region is one that is difficult to study numerically, observationally, or in situ, so it is important to develop this technique of probing the velocities in this region of comets.

Further down the tail, at a distance approximately comparable for this comet to the location of the cross-tail trajectory of the ICE spacecraft for comet Giacobini-Zinner, a possible discontinuity in the slope of the distance-velocity curve is apparent. This discontinuity is best observed in the spectrum from 1 December 1992 at a distance of about \(15 \times 10^4\) km, and it can also be seen between 10 and \(40 \times 10^4\) km in most of the other spectra. The discontinuity is better observed in the acceleration, plotted in figure 4. These accelerations were determined by smoothing the velocities in figure 3 and calculating the instantaneous acceleration at each point. The velocity slope discontinuity is the point where the slope of the acceleration suddenly decreases. For the spectrum of 30 November 1992 the acceleration itself even begins to decrease and goes to zero. These discontinuities could be due to more slowly accelerating discrete structures in the tail and not actually represent changes in the bulk flow. In this case we would expect to see these structures in images of the plasma tail. In the future we hope that simultaneous spectroscopy and imaging of the plasma tail will reveal the nature of these features.

Near the end of the observable tail still another change in the acceleration is visible. In three of the spectra, at a distance of about \(3 \times 10^6\) km the acceleration begins once more to increase quickly. The MHD simulations are not enlightening at this point: Schmidt and Wegman [1991] predict a smoothly varying velocity of around \(80 \text{ km s}^{-1}\) at this point, while the measured velocities are only around \(20\) to \(30 \text{ km s}^{-1}\). Measurements of the flow in comet Halley at this distance by Scherb et al. [1990] show that the velocity is highly time variable, ranging between about \(20\) and \(60 \text{ km s}^{-1}\), but again the Halley measurements do not have sufficient spatial resolution to discern the discontinuity in the acceleration. The physical mechanisms responsible for the acceleration discontinuities are unknown, but we hope
Conclusions

We have shown that it is possible to obtain high quality cometary plasma data from the ground. Although the current observations do not have sufficient spatial resolution to resolve the ionopause region, nor do they extend far enough in the sunward direction to study the predicted cometopause transition, the observational techniques can be extended to allow both of these possibilities. The spatial resolution achievable with our instrument was approximately 9 arc seconds, but for a brighter comet we could achieve a factor of four higher spatial resolution by not binning the CCD chip. For comet Swift-Tuttle, this increase would give a resolution of about 2500 km, allowing direct observation of the ionosphere. Obtaining data outside of the cometopause is more difficult, but it is possible that an observational emphasis on the sunward rather than tailward side of the nucleus would allow detection of these $H_2O^+$ emissions.

Ground based cometary observations like these will remain the best method of systematic study of comets, for although they generate neither the excitement nor the wealth of data of a spacecraft encounter, they are the only current method that allows both the long term study of single comets and systematic study of comets as a class. And with the prospects for any new in situ measurements in the near future quite small, ground based observation will remain not just the best, but the only method of studying comets at all.

Interpretation of measurements such as these from complicated objects like comets is difficult at best. All too often (as is frequently the case for this paper) the interpretation is simply a comparison between the observations and numerical models, showing where the model does and does not agree with the observations, and since the models are quite complex and comet-specific, even this method is not usually possible except for a small number of comets. If we are to study comets as a class, we must have truly generalizable theories to which we can compare the data and make appropriate interpretations. We therefore urge the continued development of both systematic ground based observation and the theory with which to interpret these new data.

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References


M. Brown, C. Johns, and H. Spinrad, Department of Astronomy, University of California, Berkeley, CA 94720.

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