PREDICTIONS OF THE SOLAR WIND INTERACTION WITH COMET GRIGG-SKJELLERUP

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Abstract. The planned encounter of the Giotto spacecraft with comet Grigg-Skjellerup on 10th July 1992 promises to extend our knowledge of the solar wind interaction with comets substantially. While there have been spacecraft missions to comets before now, this mission is exploratory in the sense that the target comet is much older and therefore it has a much lower gas production rate than comets Halley (by a factor ~200) or Giacobini-Zinner (factor ~10). Here we present theoretical predictions for the location of the bow shock and contact surface features, and compare similar predictions with the observed features at the previous encounters. We discuss the applicability of fluid-type theory which these models employ, in the case of strong and weak comets in the solar wind.

Introduction

Escaping cometary gas when photoionized by sunlight (scale length $\sim 10^6$ km) interacts with the solar wind electromagnetic field. The initial velocity distribution of the newly injected, and relatively heavy (mainly water group) cometary ions is unstable and causes plasma turbulence as it evolves via a ring-beam to a shell and thence towards a Maxwellian form. The cometary ions are thus accomodated into the solar wind flow. This "ion pickup" process mass loads the flow causing it to slow, and the embedded magnetic field drapes around the comet [Alfvén, 1957]. If the mass loading occurs quickly enough a collisionless shock may form when the mean molecular weight reaches a critical value. The cometary "obstacle" causing the shock is thus extremely diffuse.

The existence of the cometary bow shock has been questioned in theory [e.g., Wallis, 1973], and in some hybrid simulations [Omidi and Winske, 1987]. Other such simulations [Galeev and Lipatov, 1984] do predict a shock, as do novel fluid approaches [Zank and Oughton, 1991; Khabibrakhmanov et al., 1991]. Analyses of observations at comet Giacobini-Zinner [e.g., Smith et al., 1986*a*; Thomsen et al., 1986] were complicated by the fact that the shock width of a few cometary ion gyroradii (~10^4 km) was of the same order as the entire interaction, but subsequent analysis [Smith et al., 1986*b*] indicated the existence of a shock. The Halley observations were interpreted as shock-like [e.g., Johnstone et al., 1986; Neubauer et al., 1986; Mukai et al., 1986; Galeev et al., 1986; Coates et al., 1990] as the overall interaction size was much larger, although the shock width remained similar. At Grigg-Skjellerup, we may expect any shock to constitute much of the interaction region. The case of comets with low gas production was discussed by Flammer et al. [1991]. The plasma environment of G-S has been discussed in general terms by Neubauer et al. [unpublished manuscript, 1991]. The purpose of the present paper is to review knowledge of the cometary bow shock, and hence to predict its location at Grigg-Skjellerup.

Theory

The magnetohydrodynamic (MHD) equations describing the 1-D massloaded solar wind plasma flow in the vicinity of a comet may be solved upstream of a critical point at which the total contaminated mass flux reaches 4/3 times the undisturbed solar wind value [Biermann et al., 1967]. It was shown that the mass flux ratio at which a shock actually forms varies with the cometary gas production rate in a 2-D simulation by Schmidt and Wegmann [1982], and in all cases their ratio is $< 4/3$.

An MHD solution for the sub-solar standoff distance of the shock is given by [Galeev et al., 1985]

$$R_{\mathrm{sub}} = \frac{Q\, m_i}{4\pi\, L\; m_{sw}\, n_{sw} u_{sw}\; [(\widehat{\rho u})_c - 1]} \tag{1}$$

where Q is the gas production rate, and $L = V_e/\nu$ is the ionisation scale-length for cometary neutrals escaping with velocity V_e and an ionisation rate ν. The masses of the cometary and solar wind ions are m_i and m_{sw} respectively; u_{sw} is the solar wind speed, n_{sw} the solar wind density, and $(\widehat{\rho u})_c$ is the critical mass flux ratio $(\rho_{sw} u_{sw} + \rho_i u_i)/(\rho_{sw} u_{sw})$ where mass density $\rho = mn$. The cometary heavy ion mass flux is $\rho_i u_i$ and a constant solar wind mass flux $\rho_{sw} u_{sw} = \rho_\infty u_\infty$ is assumed. Note that this particular solution assumes that the shock standoff distance is much less than the ionisation scale-length L [Coates et al., 1990]. This is not true at comet Halley (where $L \sim R_{\mathrm{shock}}$), and equation (1) is inappropriate in this particular case.

The cometary ion flux in the vicinity of the comet may be calculated at any position (x_0, y_0), from the following integration upstream along a flow line from the point of observation [Huddleston et al., 1990]:

$$n_i u_i = \frac{Q}{4\pi L^2} \int_{x_0}^{\infty} \frac{1}{(x^2 + y_0^2)} \exp\left[-(x^2 + y_0^2)^{\frac{1}{2}}\right] dx \tag{2}$$

Here the distance, r, from the comet, and the integration path, dS have been scaled according to $r = (x^2 + y^2)^{1/2} L$ and $dS = L\, dx$. The x-axis is directed towards the Sun along the flow line. Equation (2) has been used by Huddleston et al. [1990] to obtain an innermost limit to the shock profile at comet Halley, for a critical mass flux ratio of 4/3, i.e., when $m_i n_i u_i = \frac{1}{3} m_{sw} n_{sw} u_{sw}$. For the Q-dependent critical ratios of Schmidt and Wegmann [1982], equation (2) may be used to give an estimated shock standoff at positions (x_0, y_0) for which

$$\int_{x_0}^{\infty} \frac{1}{(x^2 + y_0^2)} \exp\left[-(x^2 + y_0^2)^{\frac{1}{2}}\right] dx = \frac{4\pi\, L^2}{Q}\, [(\widehat{\rho u})_c - 1]\, \frac{m_{sw}}{m_i} n_{sw} u_{sw} \tag{3}$$

so that R'_{sub} estimates may be obtained for $y_0 = 0$.

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The standoff distance of the contact surface bounding the magnetic cavity ($B = 0$) has been estimated from MHD model approximations. Based on a balance between an outward ion-neutral drag force and an inward $\mathbf{j} \times \mathbf{B}$ force, Cravens [1986] obtained:

$$R_{CS} \approx 1.07 \times 10^{-17} \frac{Q^{3/4}}{B_S} \tag{4}$$

where B_S (in units of Gauss) is the field strength at the magnetic barrier just outside the contact surface. An estimate of B_S may be obtained from $B_S^2/2\mu_0 = m\, n_\infty\, u_\infty^2$, the stagnation pressure of the solar wind (ignoring curvature force), since at this point all the solar wind kinetic pressure has been transferred to magnetic pressure.

More sophisticated formulations for R_{CS} have been devised [e.g., Flammer, 1991; Mendis et al., 1986, Ip and Axford, 1990], however we would need to assume values for many parameters involved (on limited information for G-Z and G-S) and our calculations would not reflect the accuracy of the models. Thus we will obtain approximations from the simple and convenient form in equation (4).

Cometary Characteristics and Shocks

We now compare the gas emission characteristics for comets Halley, Giacobini-Zinner and Grigg-Skjellerup, and obtain predictions for the position of the bow 'shock' and the contact surface. For Halley and Giacobini-Zinner we may compare the predictions with the observed features at the time of the Giotto and ICE spacecraft encounters.

In Table 1 we list the relevant cometary parameters appropriate for the time of the encounters. For Halley shock calculations we use values of V_c = 1 km s^{-1} and $Q = 1 \times 10^{30}$s^{-1} from the mass loading model results of Huddleston et al. [1990]. This Q applies to the ions that mass load the region just upstream of the shock. For Giacobini-Zinner we use $Q = 3 \times 10^{28}$s^{-1} [Brandt et al., 1985; Ogilvie, 1985] and for Grigg-Skjellerup $Q = 3.6 \times 10^{27}$s^{-1} [Neubauer et al., unpublished manuscript, 1991]. The photoionisation rates ν_{ph} are calculated for the appropriate comet heliocentric distance R_H, according to a $1/R_H^2$ dependence, from the value of 3.34×10^{-7}s^{-1} at 1AU given by Huebner and Giguere [1980]. Total ionisation rates are obtained from $\nu = \nu_{ph} + \sigma\,(n_{sw}u_{sw})$ using a cross-section $\sigma = 2.1 \times 10^{-25}$ km^2 for charge exchange between the cometary neutrals and solar wind ions (see references in Huddleston et al. [1990]). The cometary ions are assumed to be of the water group with an effective m_i = 20 amu. We take m_{sw} = 1.15 amu for solar wind protons plus a nominal alpha particle content. At Halley the time-averaged solar wind flux was $n_{sw}u_{sw} = 2.266 \times 10^{18}$km^{-2}s^{-1}. For G-Z the flux was $n_{sw}u_{sw} \sim 2.5 \times 10^{18}$km^{-2}s^{-1} just before the inbound shock crossing [Bame et al., 1986]. In the calculations for G-S we use the range of values that has been observed in the solar wind [e.g., Schwenn, 1982], and thus we also obtain ranges for the possible ν and the shock prediction for the encounter.

We assume the gas outflow velocity is 1 km s^{-1} at all comets. Since all the encounters occur when the comets are ~1 AU from the Sun, and assuming comparable levels of solar activity, the ionisation rates are all similar and hence also the length scale $L \sim 10^6$ km; the cometary ions will reach similar distances from the nucleus at all three comets. The gas production rate Q then determines the 'size' of the 'object' as seen by the solar wind, in terms of the massloading it produces. The values of $(\hat{\rho}\hat{u})_c$ are obtained from the numerical results of Schmidt and Wegman [1982] and vary a little with Q.

The observed shocks from the encounters at Halley and Giacobini-Zinner are listed in Table 2. In both cases the spacecraft approached approximately across the flank; the Giotto trajectory at Halley was in fact at an angle of 107.2° to the Sun-comet line. The inbound shock crossing at Halley was observed between 1.16 and 1.12 $\times 10^6$ km from the nucleus [Johnstone et al., 1986; Neubauer et al., 1986]. At Giacobini-Zinner the spacecraft passed through the tail $\sim 7.8 \times 10^3$ km behind the nucleus [Brandt et al., 1985] and the shock feature was observed at a distance of around 10^5 km [Hynds et al., 1985]. At Grigg-Skjellerup the anticipated trajectory of the Giotto spacecraft is approximately North-South across the flank [Morley, 1991].

Theoretical estimates for the sub-solar standoff distance (R_{sub}) of the bow wave at comets Giacobini-Zinner and Grigg-Skjellerup are obtained from equation (1). For Halley, this equation is inapplicable; an estimated innermost shock profile according to equation (2) has been obtained by Huddleston et al. [1990] for $(\hat{\rho}\hat{u})_c = 4/3$ and the result at the Giotto crossing (i.e., on the flank) is quoted in Table 2. The standoff at the subsolar point (R'_{sub}) for Halley is estimated from equation (3) for $(\hat{\rho}\hat{u})_c = 1.17$.

The bow wave on the flank perpendicular to the Sun-comet line, $R_\perp$, was located at 1.5 times the sub-solar standoff distance for a modelled massloading-produced shock shape [Huddleston et al., 1990]. Thus we calculate $R_\perp = 1.5\, R_{sub}$ and include the results in Table 2. Our prediction therefore puts the Grigg-Skjellerup shock, should it occur, at $\sim 1 \times 10^4$ km from the comet nucleus along the Giotto path. However, it is by no means our assumption that a shock will necessarily form. At G-S, the extent of the entire region contained within our predicted shock is of the order of 2 to 3 heavy cometary ion gyroradii. Single particle motions are therefore likely to be extremely important, and a fluid description of the features may not be appropri-

TABLE 1. Cometary parameters at Encounters

	HALLEY	GIACOBINI-ZINNER	GRIGG-SKJELLERUP
V_c (km/s)	1.0	1.0	1.0
Q (s^{-1})	0.69 to 1 $\times 10^{30}$	3×10^{28}	3.6×10^{27}
$n_{sw}u_{sw}$ (km^{-2} s^{-1})	2.266×10^{18}	2.5×10^{18}	2 to 4 $\times 10^{18}$
B_S (nT)	63	77	60 to 80
Heliocentric distance (AU)	0.89	1.03	1.01
ν_{ph} (s^{-1})	4.22×10^{-7}	3.15×10^{-7}	3.27×10^{-7}
σ (km^2)	2.1×10^{-25}	2.1×10^{-25}	2.1×10^{-25}
ν (s^{-1})	8.96×10^{-7}	8.40×10^{-7}	7.47 to 11.67 $\times 10^{-7}$
$(\hat{\rho}\hat{u})_c$	1.17	1.21	1.22

For references see text.

TABLE 2. Observed and Predicted Shock Positions

	HALLEY	GIACOBINI-ZINNER	GRIGG-SKJELLERUP
Observed shock inbound (km)	1.12 to 1.16 $\times 10^6$	$\sim 1 \times 10^5$	?
Predicted 'innermost' crossing inbound (km)	0.95×10^6		
Predicted R'_{sub} (km)	0.769×10^6		
Predicted R_{sub} (km) from equation (1)		0.66×10^5	0.66 to 0.85×10^4
Predicted $R_\perp$ (km)	1.15×10^6	0.99×10^5	0.99 to 1.3×10^4

For explanations, see text.

ate. Indeed, the cometary ion flux through the interaction region according to equation (2) is not great enough to produce a shock estimate, although this does not preclude the possibility of a shock occuring. At G-Z, equation (2) gives a mass flux ratio of ~ 1.10 at $R_{sub} = 0.66 \times 10^5$ km, but for G-S at $R_{sub} = 0.66$ to 0.85×10^4 km the ratio according to equation (2) is 1.01 to 1.02.

Also we question whether or not a shock at Grigg-Skjellerup would be observable. A high level of turbulence would make the identification difficult. It was first suggested by Anderson et al. [1986] that the increased level of turbulence observed at the Giacobini-Zinner shock (compared to the Halley case) may be due to a larger local cometary ion production rate at this position. The rate $N_c(r)\,\nu$ for any position at any comet is proportional to the cometary neutral density N_c alone, assuming similar ionisation rates at the comets, and thus the level of turbulence at distance r may be expected to vary with $(Q/r^2)\exp(-\nu r/V_c)$. The local ion production rate at the position of the G-Z shock is ~ 11 times that at the Halley shock, and for G-S the ratio to Halley is 136.

The relative fly-by speed of Giotto will be $\sim$14 km/s at Grigg-Skjellerup [Morley, 1991]. This means that for our predicted $R_\perp$ standoff, the spacecraft will spend only $\sim$24 minutes in the interaction region between the inbound and outbound shocks. The implanted ion sensor will provide plasma ion data with a resolution of one distribution every 128 seconds [Johnstone et al., 1987] giving only 11 complete distributions in the possible inter-shock region. We will need to look for any shock boundaries in the magnetometer data, which has a higher time resolution of 28.24 vectors per second [Neubauer et al., 1987].

Contact Surface

Finally, we include estimates of the contact surface standoff R_{CS}, assuming an approximately spherical cavity. Note that single particle effects will also be a concern at the G-S contact surface, as well as at the shock.

At Halley, the contact surface was found to have a radius of 4.3 to 4.6×10^3 km [Neubauer, 1986]. For $Q = 1 \times 10^{30}\text{s}^{-1}$, equation (4) gives $R_{CS} = 5.4 \times 10^3$ km, but Q of Halley varied significantly around the time of the encounter [e.g., Weaver et al., 1986]. The value of $1 \times 10^{30}\text{s}^{-1}$ was appropriate for ions causing the mass-loading in the region upstream from the shock [Huddleston et al., 1990] and these ions had left the nucleus up to 10 days previously. In situ Giotto measurements within the coma gave $Q \sim 0.69 \times 10^{30}\text{s}^{-1}$ [Krankowsky et al., 1986] which gives an estimated $R_{CS} \sim 4.1 \times 10^3$ km. For G-Z we have no observations of the magnetic cavity; the contact surface clearly lies within the ICE closest approach distance of $\sim 7.8 \times 10^3$ km and should be considerably closer in than at Halley. The estimate from equation (4) using the parameters in Table 1 gives $R_{CS} \sim 317$ km. For G-S the prediction is $R_{CS} \sim 62$ to 83 km. These values are displayed in Table 3.

Conclusions

We have predicted the location of the possible bow shock at comet Grigg-Skjellerup using MHD formulations. Equation (1) was shown to give good agreement with observations at comet Giacobini-Zinner and it is also within its range of applicability at comet Grigg-Skjellerup. In the case of comet Halley equation (3) is required to predict a similar critical point in the flow, which agrees well with observations. It is interesting to note that equation (2) does not provide sufficient cometary ion flux to produce a shock estimate at either G-Z or G-S, despite the fact that observations at G-Z [Staines et al., 1991] gave heavy ion number densities of $\sim 1\%$ of the solar wind density at the shock giving a mass density ratio of ~ 1.2. Our estimate of the location of the two principal cometary boundaries at G-S are within range of the values quoted (without derivation) by Neubauer et al. [unpublished manuscript, 1991].

The use of an MHD framework for weak comets such as Grigg-Skjellerup, and possibly also Giacobini-Zinner, may be questionable due to the scale size of the inter-shock distance (less than 3 heavy ion gyroradii for G-S). However, a more accurate bow shock prediction would require a fully consistent 3-dimensional kinetic simulation of the comet - solar wind interaction which is not available at present. We would expect an even more turbulent plasma at the G-S shock than seen on the previous cometary missions. We note that the inter-shock time will be of the order of the round trip light time to the spacecraft so experiment modes will need to be set well in advance.

It is most unlikely that Giotto will sample the magnetic cavity. Its small size compared with the size of the error

TABLE 3. Contact Surface Predictions

	HALLEY	GIACOBINI-ZINNER	GRIGG-SKJELLERUP
Observed R_{CS} (km)	4.3 to 4.6×10^3		
Predicted R_{CS} (km)	4.1 to 5.4×10^3	317	62 to 83

ellipse of the spacecraft targeting means that Giotto has a very small chance of crossing the contact surface even if targeted straight at the nucleus, as currently planned. Nevertheless, we await the forthcoming Giotto encounter to explore an uncharted parameter range in the solar wind interaction with comets.

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References

Alfven, H., On the theory of comet tails, *Tellus, 9*, 92–96, 1957.

Anderson, K. A., et al., The upstream region, foreshock and bow shock wave at Halley's comet from plasma electron measurements, *Eur. Space Agency Spec. Publ., ESA SP-250*, 259–261, 1986.

Bame, S. J., et al., Comet Giacobini-Zinner: plasma description, *Science, 232*, 356–361, 1986.

Biermann, L., B. Brosowski, and H. U. Schmidt, The interaction of the solar wind with a comet, *Sol. Phys., 1*, 254–284, 1967.

Brandt, J. C., M. B. Niedner, Jr., and T. von Rosenvinge, The ICE project, *Adv. Space Res. 5*, (12), 3–16, 1985.

Coates, A. J., et al., Plasma parameters near the comet Halley bow shock, *J. Geophys. Res., 95*, 20701–20716, 1990.

Cravens, T. E., The physics of the cometary contact surface, *Eur. Space Agency Spec. Publ., ESA SP-250*, 241–246, 1986.

Flammer, K. R., D. A. Mendis, T. G. Northrop, and E. C. Whipple, A self-consistent model for the particles and fields upstream of an outgassing comet 1. Gyrotropic and isotropic ion distributions, *J. Geophys. Res., 96*, 15907–15916, 1991.

Flammer, K. R., The global interaction of comets with the solar wind, in *Comets in the Post-Halley Era*, vol. 2, edited by R. L. Newburn, Jr., M. Neugebauer, J. Rahe, pp. 1125–1144, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1991.

Galeev, A. A., and A. S. Lipatov, Plasma processes in cometary atmospheres, *Adv. space Res., 4*, (9), 229–237, 1984.

Galeev, A. A., T. E. Cravens, and T. I. Gombosi, Solar wind stagnation near comets, *Astrophys. J., 289*, 807–819, 1985.

Galeev, A. A., et al., Position and structure of the comet Halley bow shock: VEGA-1 and VEGA-2 measurements, *Geophys. Res. Lett., 13*, 841–844, 1986.

Huddleston, D. E., A. D. Johnstone, and A. J. Coates, Determination of comet Halley gas emission characteristics from mass-loading of the solar wind, *J. Geophys. Res., 95*, 21–30, 1990.

Huebner, W. F., and P. T. Giguere, A model of comet comae, II, Effects of solar photodissociative ionization, *Astrophys. J., 238*, 753–762, 1980.

Hynds, R. J., et al., Energetic ion observations during comet Giacobini-Zinner encounter, *Adv. Space Res. 5*, (12), 17–25, 1985.

Ip, W.-H., and W. I. Axford, The plasma, in *Physics and Chemistry of Comets*, edited by W. F. Huebner, pp. 177–233, Springer-Verlag, Germany, 1990.

Johnstone, A., et al., Ion flow at comet Halley, *Nature, 321*, 344–347, 1986.

Johnstone, A. D., et al., The Giotto three-dimensional positive ion analyser, *J. Phys. E, 20*, 795–805, 1987.

Khabibrakhmanov, I.Kh., A.J. Coates, and V.L. Galinsky, Singularities in mass-loaded MHD flow: The cometary bow shock, *Geophys. Res. Lett., 18*, 1509–1512, 1991.

Krankowsky, D., et al., In situ gas and ion measurements at comet Halley, *Nature, 321*, 326–329, 1986.

Mendis, D. A., et al., Comet-solar wind interaction: Dynamical length scales and models, *Geophys. Res. Lett., 13*, (3), 239–242, 1986.

Morley, T. A., The Giotto encounter with comet P/Grigg-Skjellerup, ESA Conf, in press 1991.

Mukai, T., W. Miyake, T.Terasawa, M. Kitayama, and K. Hirao, Plasma observation by Suisei of solar-wind interaction with comet Halley, *Nature, 321*, 299–303, 1986.

Neubauer, F. M., Giotto magnetic field results on the magnetic pile-up region and the cavity boundaries, *Eur. Space Agency Spec. Publ., ESA SP-250*, 35–41, 1986.

Neubauer, F. M., et al., First results from the Giotto magnetometer experiment at comet Halley, *Nature, 321*, 352–355, 1986.

Neubauer, F. M., et al., The Giotto magnetometer experiment, *J. Phys. E., 20*, 714–720, 1987.

Ogilvie, K. W., The plasma regime at comet Giacobini-Zinner, *Adv. Space Res. 5*, (12), 27–35, 1985.

Omidi, N., and D. Winske, A kinetic study of solar wind mass loading and cometary bow shocks, *J. Geophys. Res., 92*, 13,409–13,426, 1987.

Schmidt, H. U., and R. Wegmann, Plasma flow and magnetic fields in comets, in *Comets*, edited by L. L. Wilkening, p. 538, University of Arizona Press, Tuscon, 1982.

Schwenn, R., The "average" solar wind in the inner heliosphere: Structures and slow variations, *Solar Wind Five, NASA Conf. Publ. 2280*, 489–507, 1982.

Smith, E. J., et al., International Cometary Explorer encounter with Giacobini-Zinner: Magnetic field observations, *Science 232*, 382–385, 1986*a*.

Smith, E. J., et al., Analysis of the Giacobini-Zinner bow wave, *Eur. Space Agency Spec. Publ., SP-250*, 461–465, 1986*b*.

Staines, K., et al., Cometary water-group ions in the region surrounding comet Giacobini-Zinner: Distribution functions and bulk parameter estimates, *Planet. Space Sci., 39*, 479–506, 1991.

Thomsen, M. F., et al., The comet/solar wind transition region at Giacobini-Zinner, *Geophys. Res. Lett., 13*, 393–396, 1986.

Wallis, M. K., Weakly-shocked flows of the solar wind plasma through atmospheres of comets and planets, *Planet. Space Sci., 21*, 1647–1660, 1973.

Weaver, H. A., M. J. Mumma, H. P. Larson, and D. S. Davis, Airborne infrared investigation of water in the coma of Halley's comet, *Eur. Space Agency Spec. Publ., ESA SP-250*, 329–334, 1986.

Zank, G. P., and S. Oughton, Properties of mass-loading shocks 1. Hydrodynamic considerations, *J. Geophys. Res., 96*, 9439–9453, 1991.

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