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Interactive comment on "Warm protons at comet 67P/Churyumov-Gerasimenko – Implications for the infant bow shock" *by* Charlotte Goetz et al.

Anonymous Referee #2

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This is an interesting and detailed paper analysing over 300 more examples of the 'infant bow shock', a feature observed in Rosetta RPC data, following initial analysis of 2 events by Gunnell et al., 2018. The analysis principally considers that warmer, slower protons seen in the 'downstream' region of some of the examples are the main characteristics of the feature, although higher electron flux, lower magnetic field, higher oscillations in the magnetic field, and higher density (usually) were also characteristics of the region with warmer protons. The authors conclude that the plasma characteristics in the warmer proton regions are associated with 'intermediate' production rates in the Rosetta data, and are usually seen in the positive convention electric field hemisphere. They suggest that the 'infant bow shock' is an asymmetric structure and may develop into an 'ordinary' bow shock observed at stronger comets. The paper is well

written and the data analysis careful, but the current version suffers from a lack of references on earlier work on missions prior to Rosetta and some confusing features; it would be suitable for publication after some revision.

Major points for additional analysis and comment 1. The principal diagnostic is the observation of 'warmer, slower' protons, but this is not quantified in the paper as much as it could be, although visible in spectrograms. Some simple 1D analysis (building on the vm,H shown here) would allow calculation of the velocity, but the main suggestion here is that at least some analysis and characterisation of the width of the proton spectra, and the jump across the feature, would provide a quantitative indication related to temperature, which is missing from the current analysis although it is a prime diagnostic. 2. Some calculations of Mach number based on the analysis of Smith et al (1986) for comet GZ and Coates et al (1990, 1997) could be attempted for at least some of the observed 'infant bow shock' features in the data, as well as in the related simulations. This would strengthen the use of the word 'shock', and allow comparison to 'shocklets' seen in other simulations (e.g. Omidi et al). The change in velocity, magnetic field and density could be estimated sufficiently to do this. 3. In Figure 3, some of the vm,H values indicate an increase of velocity from upstream to downstream – this seems counter-intuitive for any shock

Minor points Line 23 – the text refers to a 'fully formed shock' at comets, but has this been observed by Rosetta? The references provided all relate to Rosetta. Additional references include Smith et al, 1986, Coates et al, 1990, 1996, relating to GZ, Halley and GS. Line 28 – Mass loading, deceleration and deflection were all aspects of earlier studies on Giotto and AMPTE data which are not referenced here (Coates et al., 2015, and references therein, are relevant) Line 38 – the convective electric field upstream of the comet drives the pickup process as shown in earlier studies (e.g. Neugebauer et al., 1989, Coates et al., 1990 and many other studies Line 45 – the bow shock location, formation and features have been studied in detail using data from Giotto by others also (e.g. Coates et al., 1990, 1996) Lines 54-55 – Bow shock studies at comets and other solar system objects have been more extensive than the references would indicate Line 64 – ‘proton velocity distribution becomes broader and the bulk velocity decreases’ – visible in the spectrograms usually, but needs some quantification (see comment 1 above) Line 66 typo ‘ensure’ Line 69 – please specify the ‘similarity to a bow shock at a fully developed comet’, using references from earlier missions – which changes were seen before and which are different here Line 83 – ‘Often, the signal is still visible in the RPC-IES instrument’ – presumably due to different FOV, please add a comment Line 93 – ‘partially complementary to ICA’ – please specify the fields of view and extent of overlap/complementarity Line 115 – ‘need to be at significantly lower energies’ – please quantify Line 134 – ‘as stated in previous publications’ – references and precision needed Table 1 -would be useful to define and include a parameter/measurement associated with the width of the proton distribution, especially as this is one of the major diagnostics of the events (again, see comment 1 above) Line 157 – It is interesting that the alpha particle and He+ spectra follow the proton distributions yet both remain distinct, another indication that the transitions are weak, a comment could be added on this Line 163 – More precise to say ‘is more negative’ rather than ‘lower’ Line 164-5 – ‘the lower the spacecraft potential, the higher the density’ could be reworded ‘higher plasma density would increase the flux of electrons to the spacecraft, providing more negative spacecraft potentials’ Line 165 – ‘This the density is higher’ – how much higher, and where? How is this visible in the data shown? Fig 2 caption – add comment (see definitions in text), or add a short explanation for the definition of the parameters shown Line 178 – ‘transition can sometimes be very broad’ – can this be quantified e.g. with respect to the electron, proton and heavy ion gyroradius? (see e.g. Coates et al. 1990) Line 190 typo ‘where’ Line 200-215 – the authors could usefully define and calculate a parameter associated with the width of the proton distributions (as with the velocity change vm,H this is a key indicator) – see also comment 1 above Section 3.3 general comment – is there any evidence for larger/more developed jumps with increasing Q? Line 224 – as well as Deca et al, there were earlier papers on momentum balance in the AMPTE releases and in comets (see Coates et al. 2015,

and references therein, eg Coates et al, JGR 1986, Johnstone et al., Geophys Monograph 38, 1985, Coates et al, Adv Space Res 1988)) Line 238 – ‘protons with higher temperatures’ - this should be quantified, see comment 1 Line 242 – ‘flux of electrons does increase downstream’ – might some of this be associated with spacecraft potential changes? Line 250 - ‘different for electrons and protons’ – and heavy ions? Line 254 – Might shocklets (e.g. Omidi et al.), and/or upstream cavities, be relevant Line 262 – 10s of minutes – how might this compare to gyroperiods/radii? Line 274 – please specify/clarify/indicate on Fig 6 the times discussed (first/second half) Line 283 – ‘density of the plasma does not change significantly’ – if anything, the spacecraft potential is more negative, thus density higher, in the ‘upstream’ region in this case Line 285 – could calculate the ratio between the solar wind and the local plasma density Line 288 – it would be useful to mention the assumed gas production rate Q in simulation and for the relevant observation Line 290 – please indicate the suggested ‘IBS’ location on Fig 5 Line 294 – what is the scale of proton gyration compared to the features seen in the simulation Line 299 – Does +Ec correspond to Eparallelz as on the Figure? Line 306 – ‘not significant enough to form a large bow shock’ – rather than ‘large’ do you mean fully developed? Might there be a relation to shocklets? Line 310 – Kessel et al (JGR, 1994) also reformulated the jump conditions and determined shock normal for multiple ion shocks Line 322 – Re shock motion – as mentioned above, it should be possible to estimate the shock motion speed from the change in velocity and shock normal (e.g. Smith et al, Coates et al) Line 325 – please briefly explain the term ‘caustic’ Line 334 – re Comet Interceptor, depending on the gas production rate of the target comet, any observed cometary bow shock may be more fully developed than the features discussed here Line 340 – also, 3D fully kinetic simulations would be valuable Line 345 – refers to a ‘density proxy’ – is this the spacecraft potential? In Fig 6 the density appears higher upstream Line 355 – More accurate to say ‘It may be that the ‘infant bow shock’ is the low production rate manifestation of what becomes the more developed cometary bow shock as observed at larger comets such as Halley’ (add references). Also discuss shocklets in this context Line 357 – ‘ordinary’ may not be the correct adjective for the complex bow shock structure, with changes at proton and heavy ion gyroscales, as observed at comets such as Halley (e.g. Coates et al., 1987)

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