Reply to Referee #1 on the manuscript Thermospheric shock waves and lensing of light in the Barium Release, Optical and Radio rocket experiment", by Leyser et al.

We thank the referee for the constructive comments on the manuscript. We have discovered an error in the data analysis concerning the lensing effect so that we are not convinced of its presence any longer. All text and one figure concerning the lensing has therefore been removed. Also, the reference to lensing in the title has been removed. However, this does not affect the main theme of the manuscript, namely the results on the shock waves themselves. Below is our response to the comments in the review report.

1. A brief review of the scientific purpose of the BROR experiment has been added in the Introduction. However, a more detailed overview of previous experiments than that already given, and also to add both Zhu et al. (2020) and Fletcher et al. (2023) which are on plasma effects from barium release experiments, is beyond the scope of the present work. As described in the Introduction, the present manuscript is on effects in the neutral thermosphere, not on plasma (or ionospheric) effects. Although the main goal for the BROR experiment was the ionospheric and electrodynamic effects, it would side track too much to review these in addition to neutral gas effects that are the subject of the present manuscript. The reference to Taki et al. was included already in the original manuscript for the main goal of the BROR experiment.
2. Figure 1 has been added to show the geometry of the experiment as relevant to the present study. Additional information on the BROR experiment and conditions has been added in the text, mainly in the Introduction and the first paragraphs in Observations. However, as mentioned above the focus of the present manuscript is on local effects in the neutral thermosphere immediately following a barium release, it is therefore not relevant to give an overview of the global characteristics of the BROR experiment. This is the topic of the paper by Taki & al. which is on ionosphere-magnetosphere coupling and which is referred to, and possibly other papers to come. However, all data has been given that is needed for the purpose and level of accuracy in the present treatment.
3. The section Discussion was accidentally numbered as a subsection to section 2, although it should be a separate section 3. This has been corrected so that the derivation of the speed of the shock waves is in section 2 (Observations) and the interpretation in terms of the radius of the copper droplets is in section 3 (Discussion). Examples of all cases are shown in figures 2-5 (Observations). In this way results obtained directly from the observations, such as the shock speeds, are kept separate (in Observations) from the interpretation of the these results in terms of copper droplets, which belongs to the Discussion. We use this structure in the manuscript for scientific clarity, to keep observations separate from the interpretation of the observations.
4. The observations are already presented individually in separate figures and in separate descriptions of the observations, although not in separate subsections. For clarity, we present examples of series of images from all cases discussed. This is then followed by presenting, again in separate figures, the speeds obtained from the series of images. We judge that to repeat the presentations in three separate subsections, one for each release, would introduce repetitions that would make the text less fluent. Also, as noted from the outset in the Introduction, previous measurements of shock waves were done only through their ionospheric effects, not directly in the neutral gas of the thermosphere as in the present study. And, as already mentioned in the Introduction, the previous observations of shock waves through their ionospheric

effects were from much larger and more powerful rockets than the BROR rocket. Taken together, a further comparison with previous measurements is not possible.

5. We do not understand this comment. The observations are repeated in this section and interpreted in terms of shock waves due to sprays of copper droplets in the neutral thermosphere (so no electrodynamics is involved for our interpretation).
6. We do not understand this comment. The observations and our interpretation are summarized. We have changed the section heading from Conclusions to Summary, to be more consistent with the content of the section.
7. The link to the video from the Sodankylä camera has been updated. In the revised manuscript the link to the video from the Vittangi camera on the lensing effect has been removed, as mentioned above.

Reply to Referee #2 on the manuscript Thermospheric shock waves and lensing of light in the Barium Release, Optical and Radio rocket experiment", by Leyser et al.

We thank the reviewer for the careful reading and constructive comments on the manuscript. We have discovered an error in the data analysis concerning the lensing effect so that we are not convinced of its presence any longer. All text and one figure concerning the lensing has therefore been removed. Also, the reference to lensing in the title has been removed. However, this does not affect the main theme of the manuscript, namely the results on the shock waves themselves. The section Discussion was accidentally numbered as 2.1 and is now given the separate section 3. The section Conclusions has been renamed to Summary, to reflect its content. Below is our response to the comments in the review report.

Introduction:

Information has been added for the original purpose of the BROR experiment as well as the usefulness of optical imaging of barium releases. Some additions to highlight the usefulness of barium-release experiments have been made. A note has been added at the end of the Summary on that the shock wave observations do not interfere with those of the barium clouds, because of different time scales. However, the significance of the observations of the shock waves is still an open question to us, but we feel that the observations are interesting enough to motivate publication.

The line numbers below refer to those of the original manuscript and the referee report, which may be different in the revised manuscript.

Line 12: Local time has been specified.

Line 24: The relevant electric field component has been clarified. It is understood that an electric field has both amplitude and direction.

Line 40-42: A figure showing the geometry of the experiment has been added as figure 1. However, the terminator is difficult to show as its altitude profile is difficult to depict in the projection of a 3D landscape on a 2D figure. We have instead given additional information on the terminator in the first paragraph in the Introduction.

Observations:

The unfortunate placement of the figures is a feature of the manuscript style used. The figure placements generally are more appropriate in the published version. Additional details of the rocket experiment pertinent to the present study have been added, primarily in the beginning of Observations. Information on the duration of the flight is given in the captions of figures 3, 4 and 6 which state the times after launch for the depicted releases. We have now also added the times after launch for the first and last barium ejection in the first paragraph in Observations, which are a measure of the ballistic flight time.

Figure 1: We have added that it is the ballistic rocket speed that is shown, so the altitude dependence of the speed is approximately the same on the upleg and downleg.

Lines 86, 87: A note on the rocket rotation (40°/s) has been added in the second paragraph of the Observations and that no effect of the rotation can be discerned in the

optical data for the barium cloud nor the shock waves. The direction of the ejecta relative to the rocket has now been more detailed in the second and third paragraph in Observations. This information is repeated where relevant in the Discussion, as in the original manuscript. However, as we know too little about the actual range of directions in which the barium was ejected, we cannot say more than what is already stated (that the ejection occurred approximately in the direction of the rocket nose) and therefore refrain from providing a cartoon of this. In view of the rocket having a much higher speed than that of the ejected remnants relative to the rocket, we only consider the direction of the rocket speed and trajectory in our simplified analysis of the shock wave speed.

Line 96: An additional panel has been added to figure 4 to show the line along which the light intensity curve of the shock is taken.

Line 98: The video frame rate of 10 fps has been added in the first paragraph of the Observations.

Lines 105-106: All velocities are now given in m/s.

Line 107: The sentence has been reformulated.

Line 118: Done.

Line 147-148: As mentioned above all results related to lensing has been removed.

Line 185: We have reformulated the sentences. With ”wind” in the original manuscript we meant the air resistance due to the motion of the rocket. The thermospheric conditions were quiet in this early part of the experiment and the background thermospheric wind is assumed negligible relative to the rocket speed. The conditions developed to the storm only later in the evening. We have now added in the second paragraph of Observations that nearby aurora did not affect the images of the shock waves.

Line 196, 198, 199, 225 to 227: Done.

Line 203: We have added information on the direction of the rocket velocity to clarify.

Lines 235-236: The reviewer is correct in that the frictional force is proportional to the size r. But the deceleration due to this frictional force is inversely proportional to the mass, according to equation (10), and the mass too depends on r. This is why a heavier particle is decelerated less by friction than a lighter particle, although the frictional force is larger on the larger and heavier particle.

Line 236: The sentence has been clarified.

Line 243 (equation 14): The purpose of the paragraph is not to strictly calculate the Reynolds number itself and demonstrate that Re $<<1$, but the purpose is only to check for consistency. We are aware that the reasoning is not logical. But if the Reynolds number would not be small with the obtained diameter L, although we had assumed $Re<<1$, we would have a problem. The consistency that we checked for is a necessary requirement, although not sufficient. We have reformulated the paragraph to bring this out.

Lines 288-289: As mentioned above, we discovered an error in the data analysis and are not convinced that lensing occurred. All data and discussion on this effect has therefore been removed.

Conclusions: The text is rightly a summary, rather than a conclusion. The section heading has therefore been changed correspondingly. A note has also been added that the shock waves exist during a much shorter time than the barium clouds, so that the possible effect of the shock waves on the barium clouds is likely negligible.