# *Interactive comment on* "Advances in understanding mineral dust and boundary layer processes over the Sahara from Fennec aircraft observations" *by* C. L. Ryder et al.

C. L. Ryder et al.

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"Synopsis: This is an overview paper of the Fennic missions and has two primary objectives a) Give an overview of the Fennic objectives, instrumentation, and research environment; and b) Highlights of interesting measurements and events. By and large I favor papers such as this that can give an overview of a mission. I periodically write papers such as these myself, basically trying to give an overview as to what was done and "Planting a flag" of interesting things ahead of a more substantial paper to be written. This paper by and large meets its objectives. There is great detail on the mission rationale, the research aircraft and the regional environment. Ultimately, I

can figure out what they did-which is the bottom line. Thus, I think the paper is all together appropriate for publication in ACP. This said, there are a few things that require attention. Perhaps they will not take too long to address, but they will have to require some attention to detail. Typically I do not write extensive review for these kinds of papers. The mission is the mission and if the authors want to present it in this way it is their business. But, there are a few things that the authors should consider. It is somewhere between minor and major revisions. This ambiguity is how the authors decide to deal with comments b)-d) where clearly there is something wrong. They do not invalidate the data set, which if analyzed is quite valuable. Regarding e) I can tell you that this will take probably the better part of a week of someones time. "

"a) Title versus conclusions. This paper is titled "Advances in the understanding..." However, this is not really what the paper is about. One only needs to look at the conclusions. This is a mission overview paper and spends considerable space laying out the mission and the environment. They do not present too much that I would consider "advances in understanding." This is a very important dataset. But In terms of what we know now, that we did not know earlier, it is fairly thin. There does not even exist a discussion section. Perhaps the conclusions should bulletize the major "New" finding s and backed up by a short discussion section one why these is new."

We have significantly changed the conclusions section based on this comment and that from reviewer 1. A table of the main Fennec aircraft publications has been included (Table 8), the conclusions shortened and made more concise, and the main new scientific findings to come from this paper are bulletized. We discuss each of the new findings and its merits in the relevant result sections so we do not add extra discussion and length to the conclusion, given the comments of Reviewer 1 on making the conclusions more concise on an already-lengthy article. We believe the bulletization and addition of Table 8 make the main points to come from the Fennec aircraft fieldwork and this paper much clearer.

"b) Size distribution: I think issues surrounding the troubles with wing mounted aerosol

and cloud probes borders on community wide apocrypha. Or maybe I am just the Rodney Dangerfield of aerosol science. But, as the authors well know because they referenced my 2003 paper, FSSP, CAPS etc probes cannot be used for measuring aerosol particle volume distributions in the coarse mode. This paper, and the work of Maring, as well as my 2006 and 2008 JGR papers lay this out crystal clear. The response function for scattering versus size is degenerate. Period. "

We agree that there are limitations to OPC usage. However, we consider that when operated and processed with care and attention as described below, where the key uncertainties are quantified and in combination with other instrumentation, they present results which are reliable for representing volume distributions in the coarse mode. A great deal of care and effort has been put into ensuring the size distributions from Fennec are reliable and that the uncertainties associated with them are correctly represented. Since this was dealt with in previous papers, it was not explicitly explained in this paper. Nevertheless, we recap several points below regarding instrument operation and processing. We also address each point raised by the reviewer and also the main points presented in Reid et al. (2003); Reid et al. (2006); Reid et al. (2008).

1. Cloud Imaging Probe (CIP) We would like to emphasize the use of the CIP during Fennec, for example measuring size distributions from 15 to 300 microns diameter during Fennec 2011. The CIP utilizes light shadowing, and therefore does not suffer from impacts of refractive index, nor from sizing by Mie theory. Despite using a different measurement technique, CIP size distributions match those of the CDP and other OPCs (Rosenberg et al. (2012); Ryder et al. (2013b)). This is strong evidence that the Fennec size distributions are not biased.

2. Great efforts were made to ensure the instrumentation used provided reliable size distributions. For example, during Fennec 2011 the CDP was cleaned and calibrated 7 times allowing bin size drift to be monitored and accounted for (Rosenberg et al., 2012), and it was found that bin edges were consistently larger than those defined by the manufacturer, which was accounted for in the data processing.

3. Scattering-Size Response Function The reviewer is entirely correct stating that the response function for OPCs is degenerate, in that a single response is possible for multiple different particle sizes. This issue was tackled in depth before this project and is presented in Rosenberg et al (2012). This methodology is summarized as follows. We consider the OPC as an instrument which directly measures particle scattering cross section and calibrate in terms of this variable. Using the uncertainty in this calibration and Mie theory with an appropriate refractive index for the measured aerosol, we derive a probability density function (pdf) which gives the probability of a particle of a particular size being counted in a particular OPC bin. Integrating this pdf allows us to derive the mean diameter and effective width of each bin. This method also permits full uncertainty propagation.

It is also of note that for dust, which is an absorbing aerosol, the amplitudes of the peaks in the response curve are much smaller than for non absorbing materials such as water. This can be seen in Rosenberg et al (2012) fig 1b. For this reason the CDP is substantially better at measuring large dust particles than it is at measuring small cloud droplets.

The impact of this thorough calibration and refractive index correction with error propagation is that the nonlinearity and degeneracy in the response curve are accounted in both the size distribution and the uncertainties as seen in figs 4 and 11. For example the sizing errors and the concentration errors in these plots take into account how the bin mid points and bin width would change if the bin boundaries were altered within the uncertainties from the calibrations. It can be seen that the horizontal sizing errors are particularly large in the smallest CDP bins (3-10 microns diameter) which reflect the weaker relationship between particle size and CDP voltage in this size range and include the impact of the nonlinear non-monotonic Mie curve.

4. Impact of refractive index on inferred particle size. Uncertainties in size distribution due to different assumptions of refractive index have been calculated and are described in Ryder et al. (2013b). They were performed by following the process in point 3

with different refractive indices and examining the results to determine the sensitivity of the size distribution to the refractive index used. In the error bars in Figures 4 and 11 we used an imaginary part ranging from 0.001i to 0.003i, since other airborne data suggested that these values were most appropriate for dust encountered during Fennec. The real part of the refractive index was assumed to be 1.53. Values of 1.42 to 1.58 were also tested, but were not found to have a significant impact on the results.

5. Lack of size distribution variability from OPC measurements Flight-to-flight differences in size distribution were significant during Fennec. This can be seen in various plots in Ryder et al. 2013a and 2013b, where effective diameter ranged from under 2 $\mu$m to over 20 $\mu$m. Figure 4 in this paper clearly shows contrasting size distributions where the peaks can be either narrow and centred upon 10 microns diameter or broad across 10 to 70 microns. The OPCs are clearly responding to different ambient distributions. This is also demonstrated in Ryder et al. (2013a). Thus we consider that the instruments were indeed responding to real changes in ambient size distribution.

6. Dust non-sphericity and impact on sizing We have not performed corrections for particle shape (away from spherical) as shape metric analysis has not yet been performed within Fennec; plans for this are scheduled. Corrections for particle shape during GER-BILS (Osborne et al., 2011) accounting for non-sphericity did not significantly alter bin size. However, the good agreement between the CIP, a shadow-based technique, and the CDP, utilizing light scattering, suggest that errors due to particle shape are minimal in the Fennec dust events sampled. Additionally, despite the fact that the OPCs have different side and forward viewing angles, (Grimm Technik OPCs: 30-150 plus 81-99 degrees, PCASP: 35-120 plus 60-145 degrees, compared to the forward viewing instruments: CDP: 4-12; SID2H: 9-20; CAS: 4-12 degrees), the size distributions agree well (e.g. Ryder et al., 2013b). This suggests that the sensitivity of the size distribution to the viewing angle during Fennec was minimal.

In terms of evidence in the literature, Veihelmann et al. (2006) provided a study on dust particle sizes using laser measurements very close to the forward scattering direction

and concluded that size distributions derived from OPCs using Mie theory are a useful estimate for true desert dust size distribution. Lacis and Mishchenko (1995) also concluded that Mie assumptions were adequate to calculate extinction from non-spherical particles. We note also that as described in Rosenberg (2012), existing data on desert dust by Volten et al. (2001) and Kahnert et al. (2007) showed that in the forward scattering regime the dust scattering phase function can be modelled by Mie theory within 20% and existing data on smaller particles show that shape has a small effect upon measurements by a PCASP (e.g. Liu et al. (1992))

7. Log Scales Log scales are useful because of the orders of magnitude of variability in concentration between the different size modes. E.g. If plotted on a linear scale, then the concentrations beneath around 1-5 microns diameter (depending on the case presented) are barely visible, which are described in the text of Section 4.1.1. These size particles are important for extinction and should not be neglected, just as the coarse and giant particles should not be either. The aerosol community regularly use log scales to display size distributions, e.g. (Haywood et al., 2005; Reid et al., 2006; Weinzierl et al., 2011; Ansmann et al., 2011; Chen et al., 2011; Johnson and Osborne, 2011).

Nevertheless, we agree that it is also useful to display the size distributions on a linear scale, as shown below for the same data as in Figure 4. We note that when lognormal modes are fitted to the data some points are outliers but most points and error bars overlap with the lognormal modes (hence the good level of agreement between parameters calculated with modal and instrumental size distributions in Ryder et al. (2013b)).

8. The key size distribution processing methodology and results are already published in Rosenberg et al. 2012 and Ryder et al. 2013b. Therefore a detailed investigation of OPC methodology is not the purpose or within the scope of this paper.

9. Radiative closure has been achieved and published recently with similar forward

scattering probes to those used during Fennec with volcanic ash and dust aerosol cases and the FAAM aircraft, when a reasonable coarse mode size distribution was encountered (Turnbull et al., 2012; Newman et al., 2012; Osborne et al., 2011). This is further evidence of reliability of these sizing probes.

"Consequently, the OPCs slightly enhance the counts of 10 um, which in the third moment, dominates the volume distribution. Additional infection points work their way into larger sizes-which are clearly visible in their size distribution plot. To recognize how big a problem this is, one merely needs to plot size on a linear Y axis (as opposed tothe log scale in this paper), and one will immediate say "Oh, that is not right: : :." I can tell that the authors know they have a problem, because in their ozone depletion comparison they compare to PCASP surface area concentration, which accounts for maybe 20% of the true surface area. "

As described in point 3 above, the work of Rosenberg et al (2012) followed in this work presents a careful method for accounting for these uncertainties and how they interact with the uncertainties from the calibrations. As the reviewer describes there is a particular inflection point around 10 micrometres diameter. In an ideal world with a perfect calibration and a perfectly described response to the dust particles we could use an inversion to correct for this. However we clearly do not live in such a perfect world and therefore the location (in terms of both particle diameter and instrument output voltage) and the magnitude of the peak/trough around this inflection point are uncertain. However, uncertain does not mean useless. This uncertainty contributes to the overall uncertainty in a nonlinear but quantifiable manner. By integrating the outcomes over variations in instrument sensitivity and particle optical properties based upon their uncertainties we can include the effect of this degeneracy upon the final uncertainty. This is accounted for in the error bars of the size distributions, which as can be seen are larger than the magnitude of any enhancements or subtractions caused by the degeneracies and which can therefore be dismissed as insignificant in the statistical sense.

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Ozone concentrations were compared only to PCASP measurements because for this specific flight the CDP had operational issues. The range displayed by the PCASP is sufficient to show the change in ozone concentrations as size distribution changes, which is the point in question.

"I get the fact that we want a coarse mode size distribution, and we have precious few tools to do that on an airplane. But please explain what is really going on. You can make the same point, by looking at ratios of the giant versus coarse mode counts, or as we showed, the FSSP/CAPS configuration makes a great forward scattering nephelometer. "

Other analysis has looked at number concentration, e.g. Ryder et al. 2013a, figure 7 and Section 4.1.4 in this paper (PCASP and CDP concentration). We have chosen the most appropriate metric to be presented in each case of analysis.

"Also, please note in my 2008 dust paper the AERONET inversions verify quite well against measured dust size distributions. Where they have a problem is past 10 um in diameter where the optical cross section is fairly low. While I cannot say the retrievals are accurate to better than 2 um, they are very precise in a single mode environment, like dust."

In the comparison referred to in Reid et al., 2008, only VMD from AERONET is presented and we note that Aerodynamic Particle Sizer measurements were also limited by an inlet with a cut-off at 10 microns diameter. We note that AERONET size distributions cut-off at 30 microns diameter (Dubovik et al., 2006) and therefore do not represent the coarse mode well, or indeed at all beyond this size. Additionally the tails of the distributions (smallest and largest particles) are constrained (Hashimoto et al., 2012) and have large errors (Dubovik and King, 2000). Therefore we agree with the reviewer that sunphotometer size distribution retrievals are challenging beyond 10 microns diameter. This is why it is of particular interest to compare aircraft to AERONET size distributions in Section 4.2.2. This topic has also previously been investigated by

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(Müller et al. (2010); Müller et al. (2012)) for dust over Morocco where discrepancies have also been found, particularly at sizes larger than around 4 microns diameter.

Changes to manuscript:

We have added a paragraph to Section 2.1.4 to describe in more detail how we have processed the size distributions to account for the various sources of error: specifically the scattering-size response function, refractive index assumptions and non-sphericity, and referring the reader to previously-published papers which give the full details of the process and assumptions made.

"c) Inlet Cutpoints and its ramification: From the above discussion on dust size I think my feelings regarding the difficulties of measuring dust from aircraft are pretty clear. Most of the results of the paper hinge on this. Along the some lines, the discussion of the inlet cutpoints and its characterization probably would benefit from some clarification. First, I would be shocked if in reality the cuptpoint were really much above 3 um. Although many have tried, I have never seen anyone be really successful. As the verification for the cutpoint is used from an OPC to OPC comparison, as discussed above the final characteristics is likely optimistic."

The Grimm OPC data shows a clear change in size distribution with drop off of the larger particles behind the inlet which cannot be mistaken for any issues associated with OPC measurements, and indeed, is evidence that the OPCs are truly responding to real changes in the aerosol size distribution (for example, see Figure 3 in Ryder et al., 2013b). Since previous scattering and absorption measurements have been made behind the BAe146 Rosemount inlets, and have often been considered to sample the coarse mode as well as the accumulation mode, it is important to quantify the inlet characteristics, as done in detail principally by (Trembath, 2012), and also Ryder et al. (2013b), which we refer the reader to in the article.

"Ultimatley, the derivation of things like AOT are likely underestimated, perhaps grossly at times when there is a large giant mode. If would actually believe the size distributions

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presented (which I don't), it would be massively so. But I would not be surprised if the AOTs were underestimated by as much as a quarter to a third on average. Similarly, absorption measurements (perhaps even more than the scattering) take a beating with inlet and plumbing losses as the single scattering albedo goes down fast with larger particle size. "

We completely agree. These were the points made and examined in Ryder et al. (2013b) with regard to the BAe146 instruments, and highlight the importance of measuring the coarse mode and its effects, in order that AOT is not underestimated and SSA is not overestimated due to lack of accounting for the coarse and giant mode. To ensure that this is not misinterpreted, the text reads, referring to Figure 6, "the measurements are restricted by the aircraft inlets, which do not sample particles larger than around 2 $\mu$m...... ... therefore the AODs presented here represent only extinction from the submicron size distribution, and are therefore an underestimate." We have added the words, "AODs are an underestimate since they do not include contribution from coarse particles" to the caption for Figure 6 to emphasize this point.

"d) Lidar: I am not a lidar guy, but it seems to be that some of the lidar data, such as in Figure 17, is massively attenuated and thus difficult to interpret other than the location top of the dust layer. It is very tough for me to make sense of it. I showed it to some lidar friends, and their immediate reaction was "Oh, that does not look right." The LNG lidar data looks ok from what we can tell. It might be worth pinging someone like John Hair at NASA Langley for an independent opinion."

The Leosphere LIDAR on the FAAM aircraft is lightweight commercial equipment allowing ease of operation and low maintenance, and thus frequent in-flight operation, with low energy output. It outputs less energy than the research prototype LNG LIDAR on the Falcon aircraft, and also has a smaller collecting receiver aperture (around 7.5cm radius as compared to the 30cm LNG mirror). The strength of the measured signal (and signal to noise ratio) will depend on both the energy output and the collecting mirror area. As a result, the Leosphere lidar signal to noise ratio is lower than that of the

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LNG. While the LNG lidar measurements are presented as extinction, the Leosphere lidar measurements are presented as range-corrected backscattered signal, of arbitrary units. Thus while the LNG lidar plots display features lower down in the atmosphere, the Leosphere range-corrected signal may not display dust features lower in the atmosphere due to attenuation at higher altitudes. In the context of cases presented in this paper, we utilize the Leosphere lidar mostly for detecting cloud tops and the tops of dust layers from above, and atmospheric structure in some cases, rather than a quantitative estimate of the aerosol load. This application is valuable in its own right, and it is not 'wrong' to use the data in this context. The exception to this is the reference to Sodemann et al. (submitted manuscript) where extinction is derived from the Leosphere lidar, and measurement resolution is decreased in order to increase the signal to noise ratio. We now emphasize and explain these points in more detail in Section 2.1.1 (LIDAR instrument section on BAe146) and in each result section referring to this data.

In Section 4.4.1 (Lidar and Dropsonde Observations) for Figure 17 the lidar data (range-corrected backscatter signal) is presented to show that the temperature inversion derived from the dropsondes at the top of the SABL coincides with the top of the dust layer. The Leosphere lidar data is absolutely appropriate for this purpose. We have added additional text to Section 4.4.1 to explain our methods in deriving features in Figure 17, which have been derived from dropsondes. Figure 17 has also been recreated based on revisions to Engelstaedter et al. (2015) (now in press) and the text in Section 4.4.1 adjusted accordingly.

Figure 7 also presents Leosphere LIDAR measurements. Here, to allow us to best present lidar data from the lower atmosphere, lidar data is plotted during the aircraft descent (beneath the sloping aircraft track, black line), where available. Above this line, lidar data from the high level flight leg is plotted. This is explained in the figure caption, and we have added an additional sentence to the figure caption to further clarify this non-canonical way of displaying the data. The description in the text (Section 4.1.4)

has also been expanded and clarified to explain the data displayed in Figure 7.

"e) Finally on figures: In my last paper to ACP the editor went after me on relatively minor issues of figure layout and clarity, requiring me to essentially redo most of the figures. Given the figures in the present paper are in much worse shape than mine, I thought I would share the love. The figures are inconsistently generated, with very hard to read color bars. Much of the time, the scales are not even listed, and at others there is over scale with lots of fine print font that will not come out well in the next typeset version. Some figures are not even labeled at all. I suggest the authors go through these all again with a fresh view and a copy of adobe illustrator. Keep in mind, ACP tends to take these full page figures and cram them into a quarter page."

We have critically reviewed all the figures based on this comment and those from reviewer 1, and list the changes to each below. Every figure is now labelled appropriately and colour bar legibility improved. In many cases we have made text larger and bolder to improve legibility, and lines thicker.

Figure 1: Contour lines made bolder, legend added.

Figure 2: Text in legend and latitude markers made bolder. Flight lines made bolder. This figure is intended to be page-width and we will ensure this is the case at the typesetting stage/proof reading.

Figure 3: Key added, contour lines made bolder, colour bar labels and plot title text made larger. This figure is intended to be page-width and we will ensure this is the case at the typesetting stage/proof reading.

Figure 4: All text and lines made bolder, text made larger, extra lines added to key.

Figure 5: Symbol added to legend in panel a. Legend made larger.

Figure 6: Circle and diamond added to key.

Figure 7: Colour bar added for lidar range corrected backscatter. a/b added. X-title text

neatened.

Figure 8: Large (mean) circles made larger as requested by reviewer 1.

Figure 9: No changes made, we consider clarity here to be acceptable.

Figure 10: All text made larger and bolder. a/b/c added to each panel. All graph lines in panel b made bolder. Distance axis removed for clarity of other labels.

Figure 11: All text and lines made bolder.

Figure 12: Colour bar title corrected to 'uplift' from 'updake'. a/b/c labelling changed to be clearer.

Figure 13: Layout changed for clarity. Flight legend placed on white box with larger, bolder text for satellite images. Date/time information larger and bolder. Bolder lines for flight tracks. Larger images for wind plots, with larger labels on colour bars and c/d/e labels. Caption changed to reflect subfigure labelling change.

Figure 14: All text and lines made bolder, legend added.

Figure 15: Panels now labelled a/b/c (previously only a/b). Caption adjusted accordingly. All plot lines made bolder, all text made clearer, larger and with consistent font within each panel. Distance axis removed for clarity of other panels. Units of extinction in c corrected following comments from reviewer 1 and adjusted to be consistent with panel b.

Figure 16: All plot lines made bolder. All text made bolder. Legends made larger and bolder.

Figure 17: Title added to colour bar. Figure data changed as described in response to Reviewer 1.

Figure 18: Units in b changed to g/kg, extra line added to panel a showing albedo 1 degree west of track.

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"Hope this helps, Jeffrey S. Reid, US Naval Research Laboratory."

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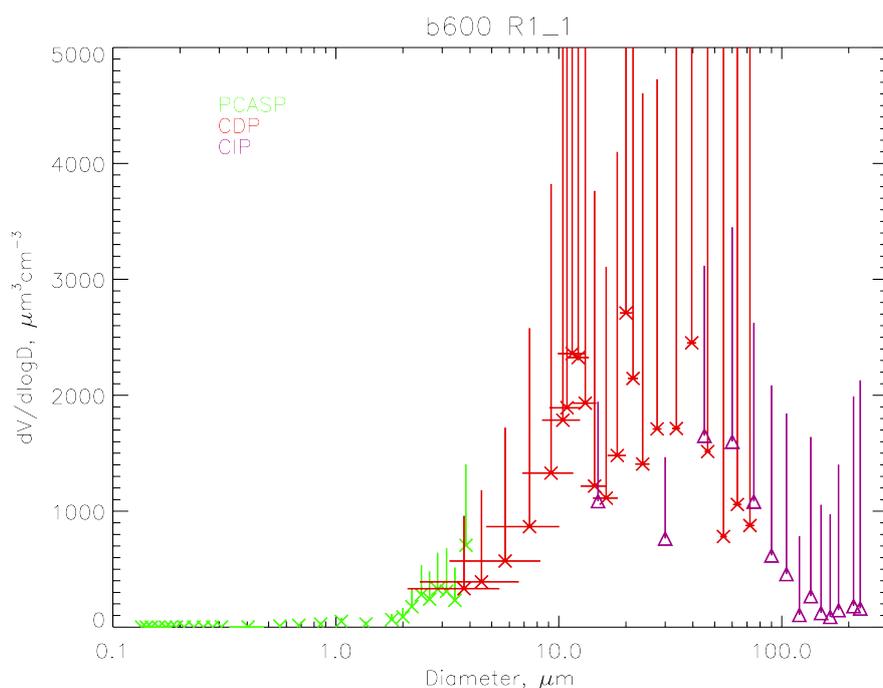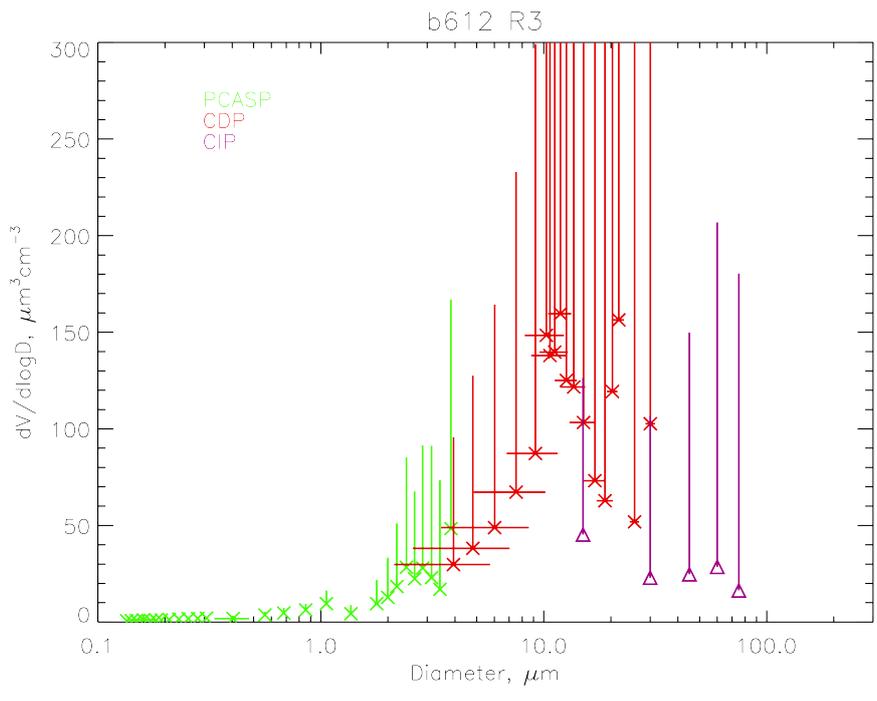Interactive comment on Atmos. Chem. Phys. Discuss., 15, 199, 2015.

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**Fig. 1.**

**Fig. 2.**

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