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# Morphology of polar mesospheric clouds as seen from space

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ABSTRACT

The Aeronomy of Ice in the Mesosphere (AIM) mission was launched in April 2007 and has completed observation of five northern hemisphere and four southern hemisphere seasons. One of the instruments aboard AIM, the Cloud Imaging and Particle Size (CIPS) Experiment produces high resolution images of Polar Mesospheric Clouds (PMCs) from space that reveal several interesting cloud structures in finer detail compared to previous space-based observations and on a larger scale than is commonly seen from ground based observations. We present the first classification of PMC structures as seen from space. Apart from Veils, Bands, and Whirls (Type I, II, and IV structures as identified in ground-based observations of noctilucent clouds (NLCs)) we also identify several structures that we denote as "Voids", "Ice Rings", "Fronts", and "Vortex-like structures". These structures are larger in scale compared to similar structures observed in ground-based NLC images. The structural similarity of several of the identified features in these space-based PMC images to those seen in tropospheric clouds and wintertime mesospheric airglow images suggests that similar processes (e.g., gravity waves, convective instability, Kelvin Helmholtz instability, turbulence etc.) influence the summer mesosphere.


## 1. Introduction

Noctilucent Clouds (NLCs) have been observed from the ground for more than 100 years. The first reliable NLC observations were reported in 1885 (Leslie, 1885). These 'night shining' clouds observed during the high latitude summer months, are visible from the ground during twilight hours when the solar depression angle is $\sim$6–15°. From space, these clouds can be observed at all hours during summer and are also known as Polar Mesospheric Clouds (PMCs). NLCs appear at $\sim$83 km and are understood to be the result of dynamically driven cooling of the summer mesopause (Lindzen, 1981) where the colder temperatures provide an ideal environment for the formation of these ice clouds. Several studies of NLC and PMC images have illustrated their complex spatial structure, and often reveal useful information about the properties of these high altitude clouds (e.g., Witt, 1962) and the dynamics of the polar summer mesosphere (e.g., Fritts et al., 1993; Taylor et al., 2011).

The different morphological forms of NLCs was first described by Grishin (1957) and later accepted by the World Meteorological Organization (WMO, 1970). WMO classified the various NLC forms into five main types. More recently, Gadsden and Parviainen (1996) provided an instruction book for observation of NLCs with photographs of their main types and sub-types. From this book, the four main types of NLCs and their descriptions are:

- Type I: Veils—tenuous and lacking a well defined structure and present as a background to other forms.
- Type II: Bands—long streaks arranged roughly parallel to each other or interwoven at small angles.
- Type III: Billows—arrangements of closely spaced, roughly parallel short streaks.
- Type IV: Whirls—partial or on rare occasions, complete rings of cloud with dark centers.

Gadsden and Parviainen (1996) also define a 'Complex structure' where two or more NLC forms may be seen simultaneously. Moreover, they note that the fifth type known as an 'Amorphous noctilucent cloud' are difficult to distinguish from Type I Veils and are therefore not included in recent manuals.

While visual observations from the ground are often limited to the latitudes of $\sim$50–65° and to twilight conditions, satellite images provide extended global measurements of PMCs, upto polar latitudes irrespective of solar depression angle. Several satellite measurements (e.g., Solar Mesosphere Explorer (SME), Solar Backscatter Ultraviolet (SBUV) instrument on NOAA fleet of satellites) of PMCs have

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provided valuable information about the climatology and global distribution of PMCs. A visible airglow photometer on the Orbiting Geophysical Observatory (OGO-6) satellite was the first experiment to trace noctilucent-like cloud layers across the polar cap (Donahue et al., 1972). The photometers observed a bright scattering layer near the mesopuase over the summer pole. This layer was identified as the poleward extension of NLCs. The first structures in PMC images from space was observed by the Wind Imaging Interferometer (WINDII) instrument aboard the Upper Atmosphere Research Satellite (UARS) (Shepherd et al., 1993), followed by the Ultraviolet and Visible Imagers and Spectrographic Imagers (UVISI) instrument on the Mid-Course Space Experiment (MSX) satellite. The images from WINDII taken from July 9 to August 4, 1993 (Evans et al., 1995) had spatial resolution that was too coarse to resolve finer spatial features. The UVISI instrument collected several PMC images over 26 passes over the polar regions during 1997, 1998, and 1999, and PMCs appeared as diffuse striations at ~83 km (Carbary et al., 2000). A Lomb periodogram analysis revealed periodic structures with wavelengths from ~100 to ~3000 km.

The NASA Aeronomy of Ice in the Mesosphere (AIM) satellite (Russell et al., 2009) was launched in April 2007 and is the first satellite dedicated to the study of PMCs. AIM has successfully completed observations of five Northern Hemisphere (NH) and four Southern Hemisphere (SH) PMC seasons. One of the instruments aboard AIM is the Cloud Imaging and Particle Size (CIPS) Experiment, a high spatial resolution Ultraviolet (UV) imager that provides detailed images of PMCs from ~65–85° latitude. Thus, unlike the limited coverage provided by ground-based observations, and the coarser resolution images from previous space-based observations, the images from CIPS provide an unprecedented view of PMCs from space allowing us to observe PMC structures in finer detail (compared to previous space-based observations) over the entire polar cap. The information provided by these PMC structures has the potential to improve our understanding of PMC formation and destruction, and enhance our knowledge of the polar summer mesosphere.

In this paper we present the first classification of PMC structure based on space-based images of PMCs observed by CIPS during the NH 2007 PMC season. In Section 2 we present a brief description of the CIPS instrument and data. In Section 3 we identify the main types of structure in PMCs, which have also been identified in ground-based NLC observations. We also document several large structures not commonly seen in ground based photographs as complete structures, owing to their large dimensions. We document the inter-annual and inter-hemispheric differences in observed PMC structures and the seasonal variability in PMC occurrence using data from four SH and four NH PMC seasons. In Section 4 we compare the observed PMC structures to tropospheric cloud features. We discuss and summarize our findings in Section 5.

## 2. Instrument and data

The measurement objectives of the CIPS experiment are to quantify PMC occurrence, morphology, and particle sizes. CIPS, a panoramic UV imager consists of an array of four cameras operating with a 15-nm passband centered at 265 nm. Images from the four cameras are combined to form a 'scene', with concatenated scenes forming individual orbit strips. More information about the CIPS instrument design and implementation on AIM can be found in McClintock et al. (2009).

CIPS images atmospheric (Rayleigh scattered background) and PMC radiance over the sunlit portion of the orbit, from ~40–85° latitude. The Rayleigh scattered background is removed from the measured total radiance to provide a cloud scattering signature. The removal of the Rayleigh scattered background and other image processing details are explained in Bailey et al. (2009). On the ascending node of the orbit, PMC observations are good all the way to 95° solar zenith angle (SZA) where the signal is lost due to the lack of sunlight. On the descending node, the Rayleigh background subtraction results in higher errors for SZA less than 42° and so the data is cut off at this point. The CIPS PMC images therefore contain data between 42° and 95° SZA which, during mid-PMC season (July in NH and January in SH), corresponds to a latitude range of ~65–85°.

We utilize CIPS albedo images from the version 4.20, level 2 data product, to identify and characterize PMC structures. Albedo is defined as the ratio of the scattered radiance to the incoming solar irradiance (Rusch et al., 2009) and has units of $sr^{-1}$. A description of the CIPS data products, calibration, and version 4.20 retrieval algorithms can be found online at the CIPS website http://lasp.colorado.edu/aim/documentation.html. Level 2 is the primary geophysical cloud retrieval product and is provided on a per-orbit basis. It includes the retrieved cloud microphysical parameters (albedo, particle radius, and ice water content) as well as timing, geolocation, and metadata information. The cloud properties and geolocation variables are provided at 25 $km^2$ (roughly 5 km × 5 km) spatial resolution. We also use the version 4.20, level 3c summary files to calculate the frequency of occurrence of clouds discussed in Section 3. CIPS cloud detections and albedo values have been evaluated by comparison with data from the Solar Backscatter Ultraviolet instruments by Benze et al. (2009, 2011).

Rusch et al. (2009) presented the 'first look' CIPS images of PMCs from space (using images from a previous CIPS data version) and noted the presence of structures such as 'ice rings', 'ice free regions', and 'bright spots' as seen in individual CIPS 'scenes' and daily averaged images. Here we use the CIPS images of cloud albedo from individual orbit swaths. Individual orbit images have the advantage of portraying larger features that may not be easily detected in smaller 'scenes', and may be averaged out in concatenated daily images. There are ~15 orbits per day with a ~90 min interval between individual orbits. These 15 orbits when merged together provide a daily global coverage of PMCs.

In Fig. 1, we show an example of a typical PMC image observed by CIPS on 22 July 2007 at 12:08 UT (AIM orbit number 1307). The time stamp "12:08" indicates the start time of data taking for this orbit. The dark blue background represents a ~900 km wide by ~8000 km long swath covered by the orbital pass, and the PMC albedo is represented in shades ranging from blue to white. The color scale is set so that any clouds with albedo less than $2\times10^{-6}\ sr^{-1}$ will not be plotted. The clouds cover 40.5% of the orbit swath, and the average albedo of the detected clouds is $17\times10^{-6}\ sr^{-1}$. Maximum albedo values ($>60\times10^{-6}\ sr^{-1}$) occur in the bright band-like (Type II NLC) structure seen at ~105°E and in the knot of bright clouds seen on the left hand side of the PMC image between 130°E and 140°E.

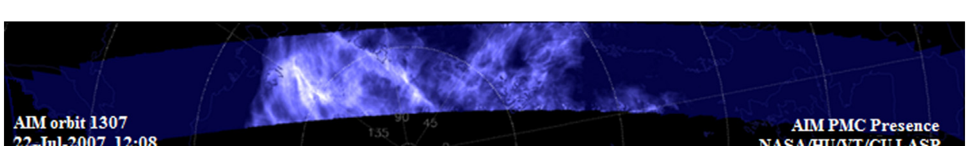


**Fig. 1.** An example of a CIPS PMC image in an orbital swath obtained on 22 July (orbit 1307) at 12:08 UT. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)