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Richard W. Schmude Jr.
Gordon State College, schmude@gordonstate.edu

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Richard W. Schmude, Jr.
Gordon State College
Barnesville, GA 30204
Schmude@gordonstate.edu

ABSTRACT

During late 2013 and early 2014, the Northern Hemisphere of Mars faced Earth. This provided a prime opportunity for studying its North Polar Cap (NPC). The writer measured the cap size during the intervals $30° < L_s < 70°$ and $82° < L_s < 134°$. (The areocentric longitude of the Sun from Mars is designated as L_s and it determines the seasons on that planet; essentially, the beginning of the northern spring, summer, fall and winter are at $L_s = 0°$, 90°, 180° and 270°). NPC latitude measurements were made with the software package WinJupos. The mean latitudes were measured for 23 four-degree intervals of L_s. Wilcoxon Signed Rank Tests at the 90% confidence level are consistent with there being no statistical difference between the NPC in 2000 and both 2013 and 2011-2012 for $30° < L_s < 70°$. Based on this same test there is a statistical difference for the NPC in 2002 and 2009-2010 compared to 2000. Therefore, it is concluded that the NPC may show interannual differences. Essentially, the NPC stopped shrinking at $L_s = 82°$. Its mean latitude for $82° < L_s < 134°$ was 81.9° ± 0.3° which is equivalent to a mean radius of 480 ± 18 km. This is nearly the same value that was measured between 1905 and 1971.

Key Words: Mars, North Polar Cap, Interannual variability

INTRODUCTION

Like Earth, Mars' axis is tilted. Because of this, its orientation changes from one year to the next. In late 2013 and early 2014, the northern hemisphere faced us. Furthermore, it was spring and summer in that hemisphere. Therefore, the North Polar Cap (NPC) shrunk and polar dust storms churned. Antoniadi (1) summarized the shrinking NPC and the albedo features in the North Polar Region (NPR). McKim (2-12) discussed the NPR between 1980 and 2007. He focused on the NPC and the North Polar Hood (NPH). James *et al*. (13) summarized Hubble Space Telescope (HST) images of Mars during 1995. They report that the cap edge at $L_s = 63.5°$ is more uneven and non-circular than at $L_s = 39.7°$ between 260° W and 360° W. James and Cantor (14) report maps of the retreating NPC in 2000 based on Mars Global Surveyor images. They also report the mean latitude of the NPC edge for different values of L_s. Benson and James (15) report mean latitudes of the NPC for different values of L_s in 2002. They also used Mars Global Surveyor images. This group concludes that there are small variations in the NPC recession between 2000 and 2002. The

difference in mean latitude for the two years is 0.9°. Cantor and co-workers (16) report that the NPC regression curves and L_s ranges are:

$L = 58.49° + 0.214\ L_s$ (~0° < L_s < ~70°) Mars Year 28
$L = 59.26° + 0.214\ L_s$ (~0° < L_s < ~70°) Mars Year 29.

In these equations L is the mean latitude of the NPC. Each Mars Year begins at L_s = 0°; Mars Year 28 started in January 2006 and Mars Year 29 started in December 2007. Therefore, the NPC in early 2006 and 2007-2008 correspond to Mars Years 28 and 29, respectively. This group did not report individual NPC latitudes but they report that the cap in Mars Year 29 had a mean latitude that was 0.77° farther north than one Mars Year earlier. Schmude (17) reports results for 2007-2012. He concludes that there was a statistical difference in the NPC latitudes (30° < L_s < 70°) between 2000 and 2009-2010. In this study NPC latitudes in 2013-2014 are reported and are compared to previous years.

METHOD AND MATERIALS

The results of this study are based on an analysis of Earth-based images made in visible and near-infrared light. Some of them were submitted to the writer but most were posted at http://alpo-j.asahikawa-med.ac.jp./Latest/Mars.htm. The software package WinJupos was used in measuring longitudes and latitudes. This software is described in Schmude (17).

A preference was given to images made in red and near infrared light because these wavelengths penetrate Martian hazes better. In some cases, RGB images were used for NPC measurements to insure full longitude coverage.

RESULTS

One goal of this study is to compare the seasonal NPC in 2013-2014 to previous years. James (18) reports that a major variable of the NPC size is the longitude. For example, Benson and James (15) report NPC maps for 2000 and 2002. Differences exceeding three degrees of latitude between the two years are evident in their Figure 2H (L_s = 48.18°). This map also shows that the NPC in 2000 was centered within one degree of the pole whereas in 2002, it was centered almost two degrees from this point. For these reasons, I report mean NPC latitudes which incorporate measurements from all longitudes. Therefore, preference is given to studies which report mean NPC latitudes. To the best of my knowledge, this leaves seven apparitions: 2000, 2002, 2006, 2007-2008, 2009-2010, 2011-2012 and 2013-2014 (14-17). The 2006 and 2007-2008 data are treated separately later since individual latitudes were not published.

In order to make comparisons between different years, the writer performed additional tasks. The mean NPC latitudes for 2000 and 2002 were read off Figure 1 in Benson and James (15). Mean latitudes for each four-degree interval of L_s were computed for both years. In 2002, no measurements were made for L_s between 48° and 57° because Mars was at conjunction. Mean NPC latitudes in 2011 for 30° < L_s < 50° were measured in the same way as in Schmude

(17). Images from Paul Maxson along with those listed at http://alpo-j.asahika-wa-med.ac.jp./Latest/mars.htm were used. Mean latitudes for 2013-2014 were also computed in the same way as in Schmude (17). These five sets of data covering $30° < L_s < 70°$ enabled me to make comparisons.

The mean NPC latitudes in 2013-2014 are similar to those in previous years. Figure 1 shows its mean latitude. The 2013 average NPC latitude (L) follows: $L = 56.3° + 0.261° L_s$ ($R^2 = 0.902$) for $30° < L_s < 70°$. In this equation L_s is the areocentric longitude of the Sun as seen from Mars expressed in degrees. The equation is in agreement with similar equations from previous years for $30° < L_s < 70°$ (13, 17). The latitude equation for 2011-2012 NPC is $L_s = 60.2° + 0.179 L_s$ ($R^2 = 0.777$) for $30° < L_s < 70°$. The variables are the same as before. The small angular size of Mars in late 2011 and 2013 is probably why the R^2 factors are lower than expected.

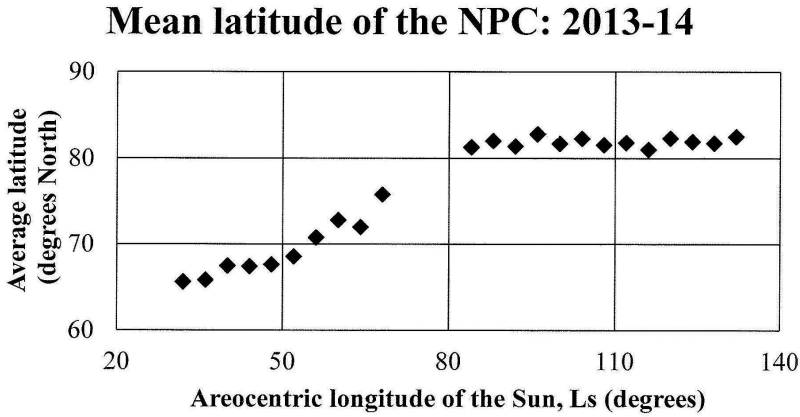

Figure 1. The mean latitude of the North Polar Cap during 2013-2014.

Wilcoxon Signed Rank Tests at the 90% confidence level were carried out for $30° < L_s < 70°$. The results are summarized in Table I. The NPC in 2000 serves as a standard for the other years. Essentially, the 2002 and 2009-2010 regression rates were statistically different than that of 2000. The NPC in 2011-2012 and 2013-2014 did not show a statistical difference compared to 2000. Therefore, it is concluded that the NPC may show interannual differences. This is consistent with the conclusions of others (15, 19).

Cantor *et al* (16) report latitude equations for the NPC in 2006 and 2007-2008 but do not report mean latitudes. Instead they report their results in terms of the dimensionless best fit radius of the circle. Therefore, I was unable to carry out statistical tests for these two years. Nevertheless, the latitudes computed from their equations were compared to the corresponding values in 2000. The results for both years lie close to those for the others in Table I.

Table I: Summary of a statistical analysis of the seasonal North Polar Cap between L_s = 30° and L_s = 70° for the years 2000, 2002, 2009-2010, 2011-2012 and 2013-2014. The analysis is based on Wilcoxon Signed Rank Tests at the 90% confidence level. The difference in mean latitude is the NPC latitude for 2000 minus the latitude for the year of interest. Values greater than zero mean that the cap edge extended farther south than in 2000.

Earth year	Statistical Difference	Difference in mean latitude (degrees)	Comparison to 2000 NPC	Mars year
2000	---	---	The standard	25
2002	Yes	0.9	Larger	26
2006	*	0.2	Probably the same	28
2007-2008	*	-0.6	Probably smaller	29
2009-2010	Yes	0.8	Larger	30
2011-2012	No	0.3	Same	31
2013-2014	No	0.0	Same	32

*Individual latitude values were not reported and, hence, statistical tests were not carried out.

Beginning in 2014, the NPC began breaking apart and its rate of shrinkage probably changed. During early January the resolution of Earth-based images was often insufficient to resolve the two classical bright areas Olympia and Ierne from the NPC. Furthermore, longitude coverage was not complete for L_s = 78° to 82°. Therefore, no measurements were made for 70° < L_s < 82°. Mean NPC latitudes were measured for 82° < L_s < 134°. The latitude essentially remained unchanged during this time. The mean latitude was 81.9° ± 0.3° N which corresponds to a mean radius of 480 ± 18 km. This is consistent with the latitude determined from photographs taken between 1905 and 1971 (20). There are times, however, when the residual NPC was smaller than the value reported here. For example, Parker *et al* (21) report that the latitude of the residual NPC edge ranged from 83° N to 86° N. This result is based on bifilar micrometer data performed in red light. More recently, Parker *et al* (19) report that the edge of the residual NPC for 90° < L_s < 112° ranged from 83° N to 85° N. The bright projection near 70° W, 80° N, Abalos Mensa, (22) is also a source of uncertainty. I treated this feature as part of the NPC but if it is treated as a separate area then this would lead to a smaller NPC. Therefore it is concluded that the radius of the residual NPC may change but that its mean size in 2000-2014 is close to what it was during much of the twentieth century.

DISCUSSION

What causes the seasonal NPC to vary from year to year? One factor to consider is atmospheric dust. Smith (23) reports (Figure 5) the dust opacity was higher over the North Polar Cap in early Mars Year 26 (the same time the NPC was measured in 2002) than one Mars year earlier (when the NPC was measured in 2000). The higher dust opacity may have caused the seasonal NPC in 2002 to retreat slower than in 2000. A second factor which may cause year-to-year changes in NPC size is albedo. Schmidt and co-workers (24) report the albedo of the South Polar Cap is the main parameter controlling its recession rate. Deposited dust will reduce the NPC albedo. Earth-based observers have imaged dust over the NPC since 2010. The amount of dust particles in the polar ice will affect grain size which will affect albedo (25). Furthermore, dust grains in the atmosphere may serve as condensation nuclei for water vapor. This in turn may affect grain size. Finally, Mars had a higher than normal amount of water vapor in 1969 which was also when the seasonal NPC was larger than at other years between 1962 and 1997 (19). Therefore, the amount of water vapor may affect the shrinkage rate of the NPC.

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