SEASONAL VARIATION OF THE COLD AND BRIGHT ANAMOLIES ON THE NORTH POLAR LAYED DEPOSITS

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Introduction: The north polar region of Mars is a very active region, from dust storms on the scale of 5000 km to polar cliff avalanches on the scale of a few meters. In the northern winter and summer, during the formation and the sublimation of the seasonal frost cap, this region is responsible for a significant change in the atmospheric pressure [1]. Due to this, the seasonal variation of this region strongly affects variation on the entire planet. A strong understanding of this region will help us predict the future climate for Martian exploration and understand the climate in the past. There are many features and processes that are poorly classified. We focused on the Cold and Bright Anomalies (CABA), first observed by thermal observations [2,3].

The CABA are cold and bright regions that appear in visual and thermal data annually during early summer [2]. There are so named because they respond differently from their surroundings that appear to have otherwise similar properties. Equally anomalous, during late summer, the CABA rapidly undergo a reduction in albedo, over just a few hours - becoming the darkest locations on the polar cap [2,3]. We used observations from Mars Color Imager (MARCI), Thermal Emission Imaging System (THEMIS), and Mars Orbiter Laser Altimeter (MOLA) to build a timeline and interpret CABA.

CABA MARCI Timeline: Before L_s 85, the albedo of the CABA and their surroundings increases approximately linearly with time (Fig 1A) and no albedo difference is observed between the two regions (Fig 1B). At L_s 85/86, the CABA's albedo begins to diverge from neighboring regions (Fig 1B). At the same time, low albedo dust streaks related with katabatic wind activity appear near spiral troughs [4] The streaks are less prominent or not observed at the CABA locations (Fig 2A).

From L_s 97 to L_s 106/107, the CABA continue brightening, whereas the surrounding region's albedo is decreasing (Fig 1), reaching peak albedo contrast at L_s 106/107 (Fig 1,2B). Then, until L_s 130 the albedo contrast begins the decrease due to cap-wide refrosting (Figs 1B,2C). During the refrosting period, the CABA's albedo continues to increase at a linear rate however, the albedo of their surroundings increases at a faster rate (Fig 1) [5,6].

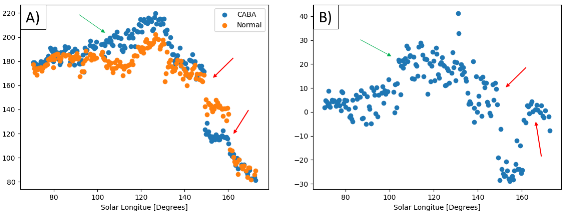

Figure 1: Relative albedo measurement of the CABA and surroundings. Data collected by taking the mean pixel value of the yellow region seen in Figure 2 and 4A. A) Relative albedo from L_s 70 to L_s 170. B) Albedo difference between the CABA and a nearby normal region. Max albedo contrast at L_s 105, green arrow, major darkening events seen at L_s 150 and L_s 161, red arrows. At L_s 160, the entire yellow region has darkened.

Around L_s 138/140, widespread dust storms are seen over the cap (Fig 2D), and some of the CABA darken quickly in a matter of hours on the scale of a few kilometers (Fig 1). The mean pixel value, which is proportional to the albedo and the reflected light, drops by a factor of 31% while surrounding remains the same (Fig 1). Other darkening events have been observed at L_s 150/151 and L_s 161/162 (Figs 1, 2E,2F). Each darkening event is more widespread, and the dust storms are more intense. From some observations, especially from MY 31 and MY 32, the darkened regions cover half the residual cap (Fig 2F).

CABA THEMIS Timeline: Before L_s 83/84, there is no temperature difference observed between the CABA and their surroundings, both regions warm linearly (Fig 3B). At L_s 83/84, the CABA begins to diverge from their surroundings and warm slower than their surroundings (Fig 3). This continues until L_s 104/105, when the temperature difference between the two region is at a maximum, the CABA are about ~20 K cooler than their surroundings (Fig 3). After this, both regions begin to cool down due to refrosting, however the CABA cool more slowly (Fig 3) [5,6]. Around L_s 140, at the time of the first darkening observed by MARCI (Figs 1, 2D), the CABA are about ~3-5 K warmer than their surroundings (Fig 3).

From THEMIS visual observations, we find that all the darkened CABA have a bright halo surroundings them (Fig 4A).

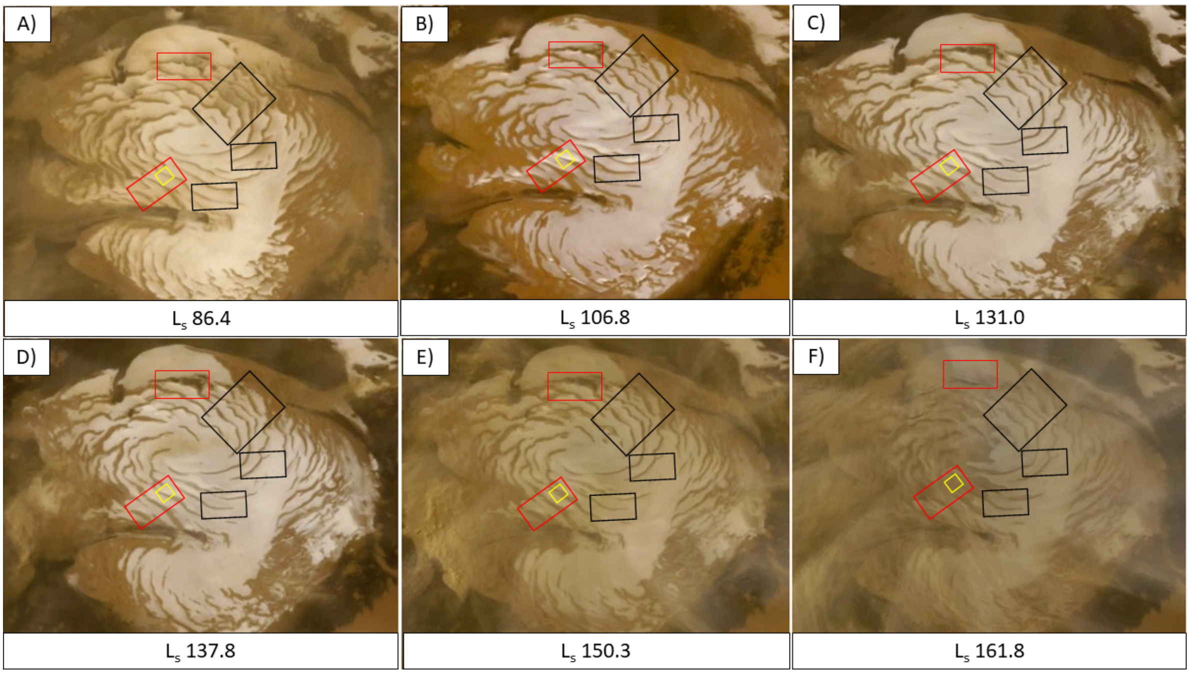

Figure 2: MARCI MY 32 observations. A) L_s 86.4, least amount of dust streaks seen at the CABA locations. B) L_s 106.8, peak albedo contrast. C) L_s 131.0, albedo contrast has decreased due to refrosting. D) L_s 137.8, first darkening event which dust storms seen around the cap. E) L_s 150.3, second darkening event with more intense dust storm. F) L_s 161.8, half the residual cap is darkened with more intense dust storm. Red outlines the most common locations for the CABA, black boxes outline the location for the strongest dust streaks and the yellow box outlines the region used for temperature and albedo observations.

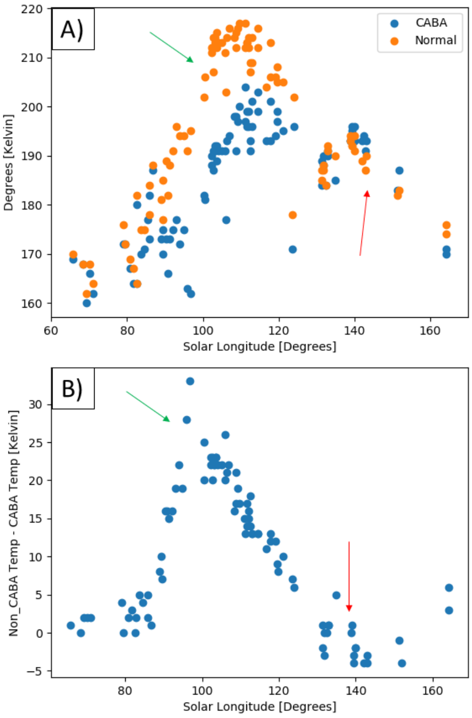

Figure 3: THEMIS temperature measurements. A) Temperature L_s 60 to L_s 163. B) Temperature difference between the CABA and a nearby normal region. Peak temperature at L_s 104 (green) the darkened CABA is warmer at L_s 140 (red). Measurements taken from regions outlined in Figure 2 and 4A.

Comparison with MOLA: The darkened CABA form on a topographic rise, ~30-50 meters higher than the surrounding terrain. In the visible spectrum, a halo is formed on either side of this rise (Fig 4B).

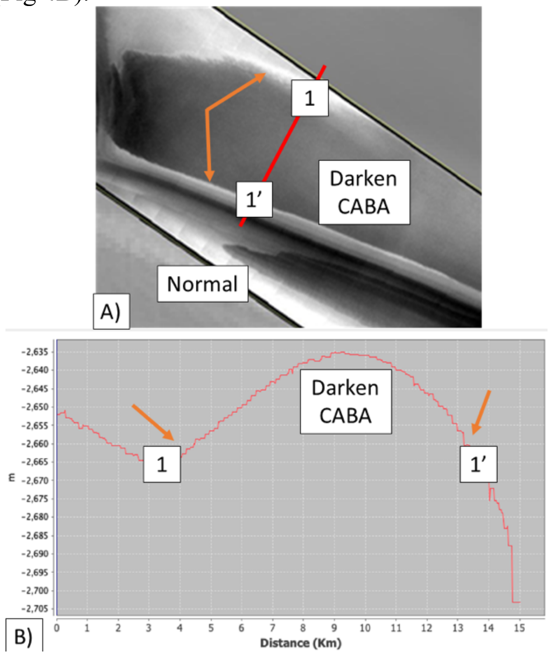

Figure 2: CABA outlined in yellow in Figure 2. A) THEMIS Visual observation (V55595018). B) MOLA topography. Halos seen surrounding the CABA, orange arrow, and found on either side of the darkened CABA.

CABA Hypothesis/Interpretation: During springtime, between L_s 70 and L_s 90 and before the

CABA are observed by MARCI or THEMIS, there are fast surface winds called katabatic winds. These winds peak at L_s 83 [7,8] and due to their proximity to the surface, they remove surface ice by two means: shear and enhanced sublimation caused by forced convection that removes water vapor [6,9]. From THEMIS observations of clouds associated with katabatic winds and from detailed Mars Mesoscale Simulations [7,9], we can see that CABA location have the slowest katabatic winds and the least amount of katabatic storm clouds (Fig 5).

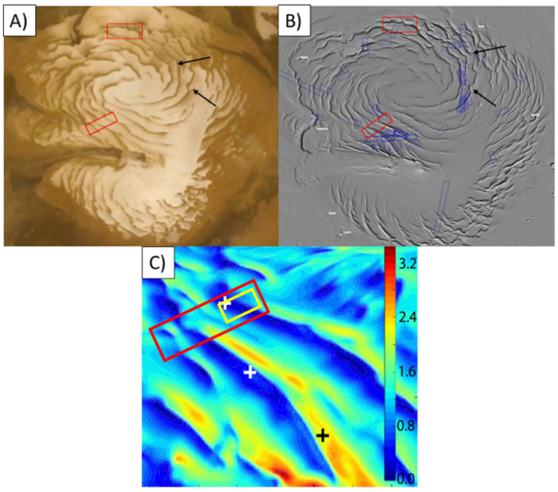

Figure 3: A) MARCI MY 32 L_s 86.4. B) THEMIS katabatic cloud observations from L_s 30 to L_s 120 C) Detailed Mars Mesoscale Simulation of the surface wind speed at L_s 50 [7], yellow region outlines the region seen in Figure 4A. Black arrows show the locations of the most intense katabatic clouds and dust streaks. Red boxes outline the most common CABA locations.

We interpret this to mean that the CABA locations are relatively calm during katabatic wind season, reducing the removal of fresh small-grained ice. Neighboring regions, that exhibit dust streaks that lower surface albedo and provide evidence for the removal of small-grained ice (Fig 6), trap more radiative flux from the Sun. For the CABA locations that retained fine-grained surface ice, the surface albedo continues to increase, which decreases the sublimation rate and provides a means by which they remain colder during summertime (Fig 3).

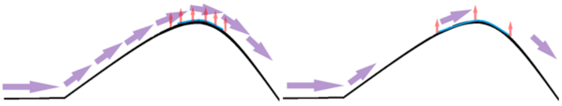

Figure 4: Heuristic model to explain the change in albedo. Greater number of arrows indicates faster winds (purple) and enhances removal of small-grained ice (red). A) Faster wind speeds lead to less surface ice and higher shear/sublimation rates. B) Lower wind speeds lead to more surface ice and lower shear/sublimation rates

During refrosting, which is a well documented period [5,6], the higher reflectance CABA act as cold traps for the sublimated water ice (Fig 7), creating a positive feedback loop and increasing the albedo and temperature contrast (Figs 1,3, 2A, B).

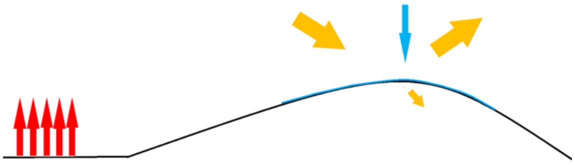

Figure 5: Heuristic model to explain the cold trapping process. Sublimated water ice from surroundings regions (red) gets condensed from the atmosphere as small-grained ice (blue). This will reflect more incoming solar flux (yellow) and create a feedback loop.

After peak mid-summer temperatures, when the cap is cooling, the CABA would cool down slower because of Newton's Law of Cooling that states the rate of cooling is proportional to the differences in the final and starting temperatures. The starting temperatures are ~200 K and ~220 K for the CABA and their surroundings respectively (Fig 3). Additionally, the albedo contrast will decrease because the CABA are already covered in small-grained reflective ice and the neighboring regions are refrosting (Fig 1, 2C).

Darkening Hypothesis: During late summer, when refrosting has stopped, we hypothesize that surface winds in part driven by large scale eddies [10] rapidly strip small-grained ice and transport them into the atmosphere, lowering the albedo by exposing dustier, larger grained ice. This happens extremely rapidly, within hours (Fig 8). This layer would be warmer than the surrounding because the heat trapped during summertime (Fig 7). Additionally, as the small-grained ice is lifted, there would be regions on either side of the topographical rise where the ice remains on the surface (Fig 8). This would be the halos seen by THEMIS visual images (Fig 4A).

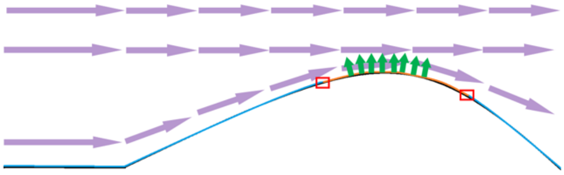

Figure 6: Heuristic model to explain the darkening process. Winds (purple) traveling over the refrosted topographical rise speed up and increase the shear rate. This removes surface ice (green) and leaving halos on either side, outlined in red.

The darkened CABA location we studied, seen in Figure 2, has areas of 136 km^2, 6,030 km^2 and 156,551 km^2 at L_s 140, L_s 151 and L_s 162 respectively. Assuming the ice layer is between 1 and 5 mm, the average grain size is 10 µm [6] and a density of 0.01 kg m^{-3} [11], we calculate the amount of ice lifted is ~4,080 kg, ~176,820 kg and ~4,519,710 kg at

L_s 140, L_s 151 and L_s 162 respectively. The mass estimation assumes once the region has darkened no more ice is removed from these locations and the areas are only calculated for the darkened areas seen by MARCI, the true number is most likely within an order of magnitude.

Future Work: In order to further test these hypotheses, we plan to study mesoscale, near-surface winds with Le Laboratoire de Météorologie Dynamique (LMD) Mars Mesoscale Model over the CABA and neighboring locations. Simulations will have resolution better than 15 km from L_s 83 to L_s 170. No high-resolution simulations have been published for each Ls date after L_s 140, leaving a void in the study of CABA and surface processes in general. We plan to use these simulations to determine wind speed, wind direction, and shear stress for removing fine grained particles. We also plan to increase visual and thermal observations of the CABA locations after L_s 140. There are few thermal and visual observations for us to use, and more observations will lead to a better understanding of factors governing the CABA.

References: **[1]** Tillman et al. (1993) J. Geophys. Res. 98, 10,963–10,971. **[2]** Kieffer, H.H. & Titus, T.N. (2001) Icarus 154, 162–180. **[3]** Calvin, W.M. & Titus, T.N. (2008) Planet. Space Sci. 56, 212–226. **[4]** Howard, A. D. (2000), Icarus, 144, 267–288. [**5**] Calvin et al (2014) Icarus. 251, 181-190. **[6]** Brown, et al. (2016) Icarus. 277, 401-415 **[7]** Smith et al. (2013) J. Geophys. Res. 118, 1835–1857. **[8]** Spiga, A. & Smith, I. (2018) Icarus 308,197–208. **[9]** Bramson et al. (2019 J. Geophys. Res. 124, 1020–1043. **[10]** Tyler, D.& Barnes, J. R. (2005) J. Geophys. Res. 110. [**11**] Whiteway et al. (2009) Science 325, 68–70.