FIRST ATTEMPT TO RETRIEVE A MARS ATMOSPHERIC WIND MAP FROM EARTH, USING VLT/UVES DURING THE 2018 GLOBAL DUST STORM.

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Abstract

This work presents ground-based wind velocity measurements of Mars during the 2018 global dust storm using Doppler velocimetry techniques based on observations made with the Ultraviolet and Visual Echelle Spectrograph (UVES) at the European Southern Observatory's Very Large Telescope (VLT) facility in Chile. This instrument's high resolution (R $\sim$100 000) allows for the dust cloud velocity to be measured, by computing the Doppler shift induced in the Fraunhofer lines (in the λ of 420-1100 nm) in the solar radiation that is backscattered in the dust suspended in the Martian atmosphere, by the motion of that same dust, with an average error of approximately 5 ms^{-1}. This allows us to sound Mars' middle atmosphere during a global dust storm and obtain latitudinal wind profiles and a first approach of a planetary wind map at the altitude level sounded, i.e. the altitude level where the optical depth reaches the unity.

Introduction

The purpose of this research project is to successfully apply and validate a new approach to investigate Mars' middle atmosphere wind velocities from ground-based observations. This is the first time that a Doppler velocimetry method based on observations made in the visible and ultraviolet wavelength range has been employed to study the Martian atmosphere.

Global dust storms are complex stochastic events that can drastically alter the atmospheric dynamics. During such events, dust can be lifted to heights above 50 km across all latitudes and longitudes, increasing the optical depth form on the sand, and consequently, the heating rates strengthen the Martian circulation. The processes that allow for the development of global dust storms are poorly understood. Furthermore, the cut-off mechanisms that spur the end of these storms are also without consensus and may even vary from storm to storm. These storms usually develop in the southern hemisphere during southern Summer and Spring (Ls $\approx$ 180° - 360°), however, the 2018 storm started developing in the northern hemisphere on Ls $\approx$ 185° (Sánchez-Lavega et al., 2019).

The martian atmosphere is extremely sensitive to the amount of dust in the atmosphere (Gierasch and Goody, 1972). Some of the consequences that increased dust loading imposes on the thermal state of the atmosphere are related with the warming of the atmosphere's layers as a direct consequence of the increased dust optical depth. Airborne dust absorbs and scatters visible radiation which acts to heat itself and its surroundings. Furthermore, the heating of the atmosphere creates pressure gradients which in turn lead to winds. The dusty season on Mars has a much more vigorous circulation - the mass flux of the Hadley circulation can even double (Haberle et al., 1993).

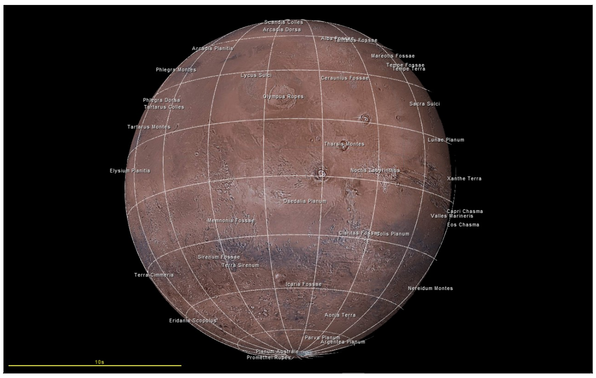

Figure 1: Topographic region on Mars covered by the VLT/UVES survey along our run of observations during the Martian Global Dust Storm on 2018.

Global dust storms are unique to Mars and are, perhaps, the most spectacular atmospheric event taking place anywhere in the Solar System. These storms induce thermodynamic responses throughout the whole atmosphere however, their occurrence is unpredictable and shows inter-annual variability, and despite the massive development our understanding of Mars has suffered over the last 50 years, these storms are still viewed as stochastic events, and the issue of their year-to-year variability remains largely unresolved.

One could see the evidence that Global dust storms do strengthen the atmospheric circulation, however, due to the low mass of the Martian atmosphere, the winds carry little momentum. Their characterisation is nonetheless crucial, as they are critical to the Martian climate, and it is important to study the atmospheric role of the energy input due to the infrared radiation absorption by the dust grains while in atmospheric suspension.

These storms can lift enough dust into suspension to dramatically increase the opacity of the atmosphere for several months, as was the case of the major global dust storm observed in 2018. A consequence example is the recent 'demise' of NASA's Opportunity Rover - which was solar powered and did not survived the 2018 global dust storm. These storms are also believed to be electrically charged, which can pose a serious threat to any operational electronic devices. Furthermore, recent findings suggest that such storms may have played an important role in Mars' loss of water (Vandaele et al., 2019, Fedorova et a., 2020).

Since surface winds are generally too weak to lift dust particles, sand particles saltation is the chief contributor to the suspension of dust. By being greater in size these particles are easier to lift, however when lifted they tend to saltate and upon their return to the surface, they impart additional momentum onto the dust, allowing for its lifting (Mackwell et al., 2013), enhancing a reinforced positive feed-back mechanism that increases substantially the amount of dust particles in atmospheric suspension. Direct suspension may also play a role, particularly in locations where sand is not abundant (Kahre et al., 2017).

Global dust storms and Martian dust cycle are among the more complex and least-understood events related to Mars' climate. These events cover large fractions of the planet with optically thick dust ($\tau_{visible}$>3) they can even envelop the entire planet. Global storms are rare and stochastic in nature - occurring in one out of three years (R. Zurek and J. Martin, 1993) - as their interannual variability is poorly understood (R. M. Haberle, 1986). There have been eight confirmed global dust storms observed (1956, 1971-1972, 1973, 1977, 2001, 2007, 2009 and 2018; Kahre et al., 2017; R. Haberle (2015); Sànchez-Lavega et al.,2019). All of these events initiated during the aphelion season (southern spring and summer) when the insolation is near peak values and the circulation is most vigorous.

Observations and Method

Unlike Venus, Mars' atmosphere is very transparent in the visible and ultraviolet ranges and the radiation in those wavelength ranges that is back-scattered in the atmosphere is negligible which precludes the application of our method. However, during global dust storms, the opacity of the atmosphere increases and allows for the scattering of enough light in the suspended dust in the middle atmosphere for the application of our method to be feasible.

The Doppler velocities were retrieved using the Doppler velocimetry technique, developed and fine-tuned at Widemann et al. 2008, Machado et al. 2012, 2014, 2017, 2021 and Gonçalves et al. 2020, for the case of Venus.

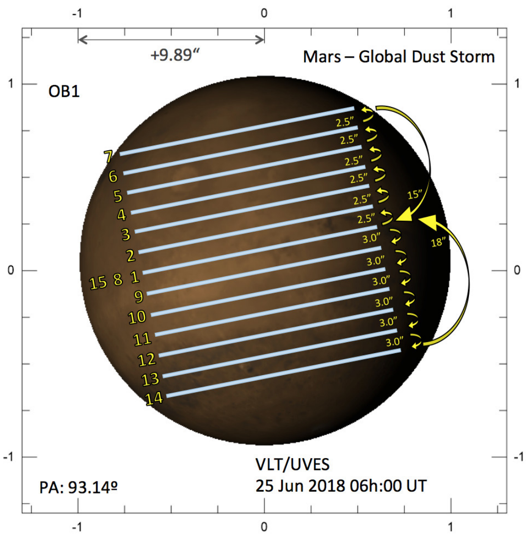

Figure 2: Scheme with the slit positions of the observations in relation to Mars, as seen from VLT at the time of the observations.

This technique was also adapted for dynamic studies upon Saturn (Silva et al., in preparation).

The adaptation of our Doppler velocimetry method for the case of Mars atmospheric studies, took into account the geometry of our observations. Spherical geometry was used to locate the observations within the planet, as seen from Earth at the time of each observation, and compute the de-projection factors for each point of the slit and for each exposure, in order to deproject the radial Doppler velocities from the observer's (Earth) line-of-sight.

The rotation velocity's contribution to the overall Doppler shift was removed by computing and subtracting the rotation velocity at each point on Mars sounded by the spectroscopic slit, that was done for all the positions surveyed on Mars. Furthermore, the contributions made to the total shift by the Young effect were evaluated and deemed negligible under the specific geometry of our observations.

The wind velocities retrieved from the motion of the dust particles in atmospheric suspension, during the 2018 Global Dust Storm on Mars, were computed and we will present the output of this work.

Results and Discussion

The scope of this work is to study the behaviour of Mars' middle atmosphere during a global dust storm using ground-based observations made with VLT-UVES and Doppler velocimetry techniques, for the first time, to complement observations of orbiter instruments. The success and validation of the application of this method

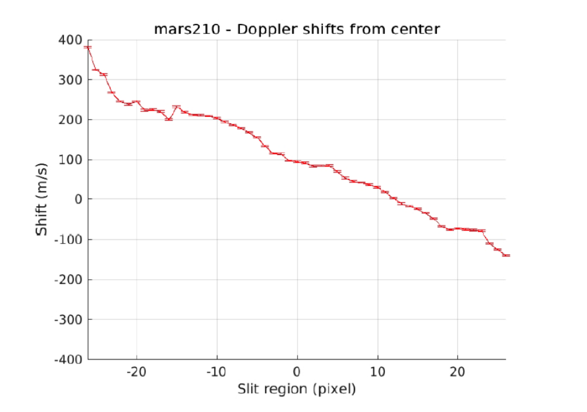

Figure 3: Raw Doppler shift retrieved at each position sensed along the spectroscopic slit (VLT/UVES).

to the atmosphere of Mars may provide a new, unique way to investigate the Martian atmosphere during dust storms.

The intent is to contribute to a better understanding of the circulation during planet-encircling dust events. We measured the wind velocity and its spatial variability, through high-resolution spectroscopy and Doppler velocimetry. The observations were made with the high-resolution spectrograph UVES at ESO's Very Large Telescope (VLT) in the visible wavelength range.

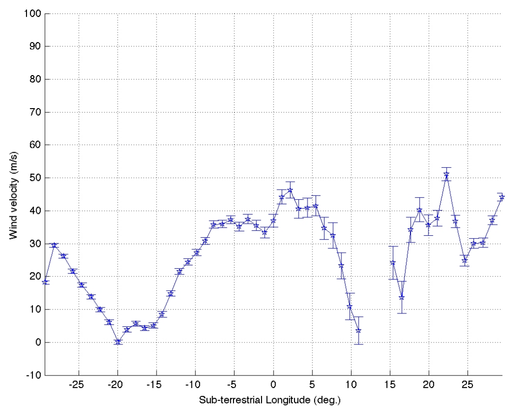

Figure 4: Example of retrieved wind velocities of dust particles in atmospheric suspension. The VLT/UVES spectroscopic slit was aligned with Mars' equator at the centre of the planetary disc, as seen from Earth.

Conclusions and Prospects

The main goal of this research line is, therefore, to provide direct instantaneous (the velocities retrieved for each pixel sounding the planet through the spectroscopic slit were obtained simultaneously) wind measurements using visible Fraunhofer lines scattered at Mars' dust hazes, which allows spatial wind variability studies and will make possible to obtain a latitudinal profile of the wind along with the cited global dust storm and a wind map of the dust storm as a function of the latitude and local time over the planet as seen from Earth.

After the success of this exploratory project, we intend to deeper explore Mars' atmosphere dynamics using this tool. The main developments are two-fold: we will sound Mars from the ground for several successive days and we will prepare a coordinated observation campaign in order to observe in the visible and in the infrared domain at the same time, that will allow us to study different altitudes in a synchronous way. Finally, it would be relevant to have access of space-based coordinated observations which will allow us to better estimate the atmospheric altitudes sensed.

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References

[1] Esposito, L. et al., Venus III, Bougher, Hunten and Philips Eds., Sp. Sci. Ser., Arizona U. Press, pp. 415, 1997.

[2] Fedorova et al., 2020. DOI: 10.1126/ science.aay 9522 https://science.sciencemag.org /content/367/6475/297.

[3] Gierasch, P.J., and Goody, R.M. (1972, Jan).The effect of dust on the temperature of the Martian atmosphere. Journal of Atmospheric Sciences, 29, 400402. doi:10.1175/15200469(1972)029<0400: TEODOT> 2.0.CO2

[4] Gilli G. et al. 2017, Icarus, Vol. 281, pp. 55-72.

[5] Haberle, R.M., et al. (1993, Feb). Mars atmospheric dynamics as simulated by the NASA Ames General Circulation Model. 1.The zonal mean circulation. Journal of Geophysics Research, 98(E2), 30933123. doi: 10.1029/92JE02946

[6] Haberle, R.M. (1986). Inter annual variability of global dust storms on mars. Science, 234(4775), 459-461. doi:10.1126/science.234.4775.459

[7] Haberle, R. (2015). Solar system/sun, atmospheres, evolution of atmospheres planetary atmospheres: Mars. In G.R. North, J. Pyle, and F. Zhang(Eds.), Encyclopedia of atmospheric sciences. Oxford: Academic Press. doi.org/10.1016/B9780123822253.003121

[8] Kahre, M., Murphy, J., and Haberle, R. (2006, 06). Modeling the Martian dust cycle and surface dust reservoirs with the nasa ames general circulation model. Journal of Geophysical Research, 111. doi: 10.1029/2005JE002588

[9] Kahre, M.A., Murphy, J.R., et al., The atmosphere and climate of mars (p. 295Ñ337). Cambridge University Press. doi 10.1017/9781139060172.010

[10] Leovy, C.B., Zurek, R.W., and Pollack, J.B. (1973, Jan). Mechanisms for Mars dust storms. Journal of Atmospheric Sciences, 30, 749762. doi:10.1175/15200469(1973)

[11] Maattanen, A., et al. (2010,Oct). Mapping the mesospheric CO2 clouds on Mars: MEx/OMEGA and MEx/HRSC observations and challenges for atmospheric models. Icarus, 209(2), 452-469.doi: 10.1016/j.icarus.2010.05.017

[12] Machado, P.(2014). Dynamics of Venus' Atmosphere: Characterization of its Global Circulation with Doppler velocimetry.

[13] Machado, P., Luz, D., Widemann, T., Lellouch, E., Witasse, O.(2012,Sep). Mapping zonal winds at Venus' cloud tops from ground-based Doppler velocimetry. Icarus, 221(1), 248-261.doi: 10.1016/j.icarus.2012.07.012

[14] Machado, P., Widemann, T., Luz, D., Peralta, J. (2014,Nov). Wind circulation regimes at Venus' cloud tops: Ground-based Doppler velocimetry using CFHT/ESPaDOnS and comparison with simultaneous cloud tracking measurements using VEx/VIRTIS in February 2011. Icarus, 243, 249-263. doi:10.1016/j.icarus.2014.08.030

[15] Machado, P., et al. (2017,Mar). Venus cloud-tracked and doppler velocimetry winds from CFHT/ESPaDOnS and Venus Express/VIRTIS in April2014. Icarus, 285, 8-26.doi:10.1016/j.icarus.2016.12.017

[16] Machado, P., et al., Two Altitude Levels Venus' Atmospheric Dynamics from Cloud-Tracking (Akatsuki and Venus Express), Doppler Techniques (Ground-Based Observations) and Comparison with Modelling, 2021.

[17] Mackwell, S.J., Simon Miller, A.A., Harder, J.W., and Bullock, M.A. (2013). Comparative Climatology of Terrestrial Planets. doi:10.2458/azurua press 9780816530595

[18] Montabone, L., et al. (2015, May). Eight-year climatology of dust optical depth on Mars. Icarus, 251, 65-95.doi:10.1016/j.icarus.2014.12.034

[19] Moreno, R., et al. (2009, Jun). Wind measurements in Mars' middle atmosphere: IRAM Plateau de Bure interferometric CO observations. Icarus, 201(2), 549-563.doi:10.1016/j.icarus.2009.01.027

[20] Pollack, J.B., et al. (1979,Jun). Properties and effects of dust particles suspended in the Martian atmosphere. Journal of Geophysics Research, 84, 2929-2945.doi:10.1029/JB084iB06p02929

[21] Pollack, J.B., et al. (1990,Feb). Simulations of the general circulation of the Martian atmosphere.1. Polar processes. Journal of Geophysics Research, 95, 1447-1473. doi: 10.1029/JB095iB02p01447

[22] Sanchez-Lavega ,A., et al. (2019).The onset and growth of the 2018 Martian global dust storm. Geophysical Research Letters, 46(11), 6101- 6108. doi:10.1029/2019GL083207

[23] Vandaele, A.C., et al. (2019, Apr). Martian dust storm impact on atmospheric H2O and D/H observed by ExoMars Trace Gas Orbiter. Nature, 568 (7753), 521-525. doi:10.1038/s41586-019-1097-3.

[24] Widemann, T., Lellouch, E., Donati, J.-F. (2008,Aug). Venus Doppler winds at cloud tops observed with ESPaDOnS at CFHT. Planetary Space Science, 56(10), 1320-1334.doi:10.1016/j.pss.2008.07.005

[25] Zurek, R., J., Martin, L. (1993, 03). Inter annual variability of planet-encircling dust storms on Mars. Journal of Geophysical Research, 98. doi:10.1029/92JE02936

[26] Zurek, R.W.(2017). Understanding Mars and its atmosphere. In R.M. Haberle, R.T. Clancy, F. Forget, M. D. Smith, R.W. Zurek (Eds.), The atmosphere and climate of Mars (p. 3—19). Cambridge University Press. doi 10.1017/9781139060172.002