Galileo's Medicean Moons: their impact on 400 years of discovery
Proceedings IAU Symposium No. 269, 2010
C. Barbieri, S. Chakrabarti, M. Coradini & M. Lazzarin, eds.

doi:10.1017/S1743921310007453

Io, the closest Galileo's Medicean Moon: Changes in its Sodium Cloud Caused by Jupiter Eclipse

Cesare Grava[1a], Nicholas M. Schneider[2] and Cesare Barbieri[1b]

[1]Department of Astronomy, Padova University,
Vicolo dell' Osservatorio, 3, 35122 Padova, Italy
[a]email: cesare.grava@unipd.it
[b]email: cesare.barbieri@unipd.it

[2] LASP, University of Colorado
Campus Box 392, Boulder, Colorado 80309-0392515, USA
email: nick.schneider@lasp.colorado.edu

Abstract. We report results of a study of true temporal variations in Io's sodium cloud before and after eclipse by Jupiter. The eclipse geometry is important because there is a hypothesis that the atmosphere partially condenses when the satellite enters the Jupiter's shadow, preventing sodium from being released to the cloud in the hours immediately after the reappearance. The challenge lies in disentangling true variations in sodium content from the changing strength of resonant scattering due Io's changing Doppler shift in the solar sodium absorption line. We undertook some observing runs at Telescopio Nazionale Galileo (TNG) at La Palma Canary Island with the high resolution spectrograph SARG in order to observe Io entering into Jupiter's shadow and coming out from it. The particular configuration chosen for the observations allowed us to observe Io far enough from Jupiter and to disentangle line-of-sight effects looking perpendicularly at the sodium cloud. We will present results which took advantage of a very careful reduction strategy. We remove the dependence from γ-factor, which is the fraction of solar light available for resonant scattering, in order to remove the dependence on the radial velocity of Io with respect to the Sun.

This work has been supported by NSF's Planetary Astronomy Program, INAF/TNG and the Department of Astronomy and Cisas of University of Padova, through a contract by the Italian Space Agency ASI.

Keywords. Planets and satellites: Io

---

1. Io's Neutral Cloud

There are three major features in the Neutral Sodium Cloud around Io: a banana shaped cloud of slowly escaping neutral atoms, a fast "jet", produced by pickup ion neutralization in Io's atmosphere and a molecular ion "stream" resulting from ionization and pickup of sodium-bearing molecules directly from Io's atmosphere. The "banana cloud" (Brown 1974) contains slow atoms escaping from the surface, and its shape is controlled by celestial mechanics and by ionization (Burger *et al.* 1999). The "stream" is composed of fast sodium atoms which are ejected from the torus by dissociation or dissociative recombination of unidentified molecular pickup ions containing sodium (NaX^+). The "jet" and "stream" showed that Io's ionosphere and Jupiter's magnetosphere interact with each other (Schneider & Trauger 1995). The Jupiter-Io system is reviewed in Schneider & Bagenal 2007.

2. Resonant Scattering

The Sodium is only a trace component in the Io's exosphere (only few %'s). But it is by far the most visible from Earth thanks to the very high cross section for resonant scattering mechanism. A solar photon excites an electron to the first excited state, and when it returns to its ground state (after nearly 10^{-7} sec) it emits a photon. The first excited state is in reality double due to fine structure, so this process can actually emit in two possible wavelengths (5890 and 5896 Angstrom for the D2 and D1 line respectively).

The γ-factor is the ratio between the intensity of the absorption line at a given wavelength and the intensity at the continuum. It is an indicator of how much solar light a Sodium electron "sees" at a given velocity with respect to the Sun. When Io is in conjunction, its relative velocity with respect to the Sun is zero, so the electrons see a very small amount of solar light, corresponding to the bottom of the Fraunhofer line. In this case the γ-factor is $\sim$ 0.05, meaning that the Sodium atoms receive $\sim$ 5 % of the solar continuum and the Sodium Cloud will be faint (right side of the Figure 1). On the contrary, when Io is at elongation, its velocity with respect to the Sun is at maximum, the atoms have more light available for scattering (the γ-factor increases up to 0.70) and the Sodium Cloud will be brighter (left side of the Figure 1).

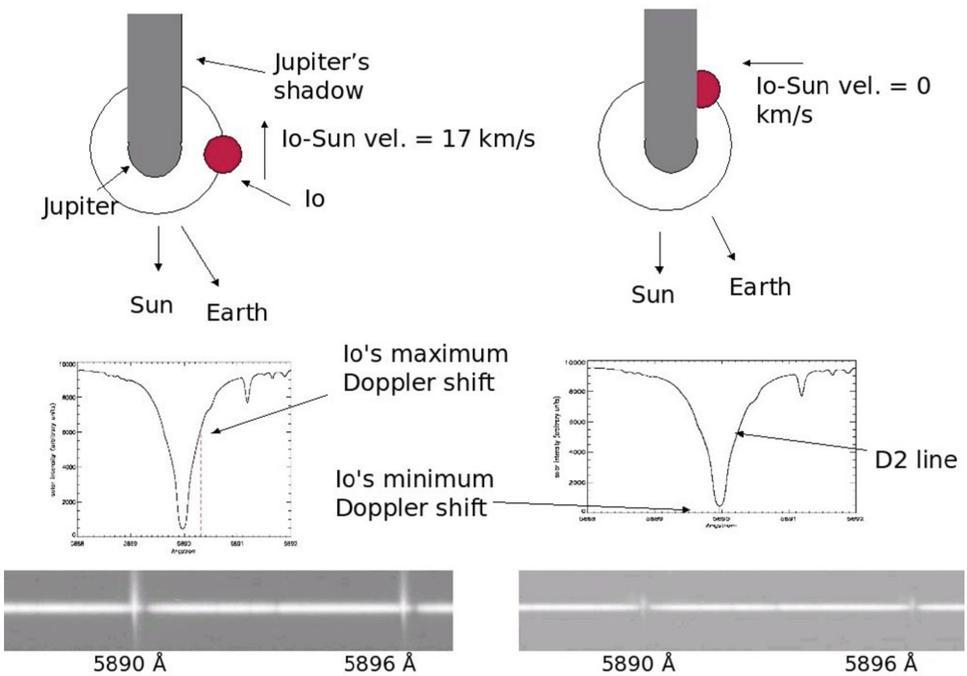

Figure 1. If the Sodium abundance is constant throughout Io's orbit, its brightness depends only on the orbital longitude. Left part: Io is at western elongation; right part: Io is at superior conjunction. Together with the geometrical configurations (upper part) there are the plots of solar radiance around the Sodium D2 line (middle) to show the dependence of the γ-factor from the orbital longitude, and the spectra of Io (bottom), showing the Sodium emission being fainter while Io-Sun relative velocity approaches zero.

https://doi.org/10.1017/S1743921310007453 Published online by Cambridge University Press

3. Scientific Goals

As the γ-factor increases after the occultation, Sodium atoms see more solar photons, and the intensity of the cloud increases. Nevertheless, some past observations showed some evidence of post-eclipse brightening, i.e. the sodium cloud immediately after the eclipse is less bright than it should be, and reaches the expected values of luminosity hours after the reappearance. One possible explanation is condensation of sulfur dioxide during the eclipse, which would prevent NaCl (principal source of Na atoms) to be released. This is the fascinating hypothesis we want to test (see Figure 2).

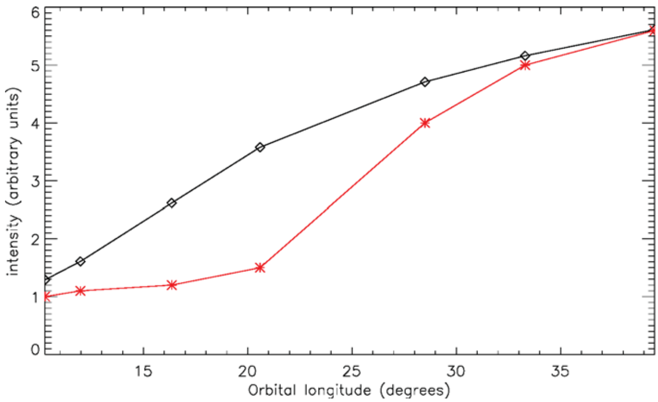

Figure 2. The expected brightness of the neutral sodium cloud. A non-condensing cloud should follow the black diamonds trend; a condensing cloud will follow the red asterisks trend, that is: starting less bright than the expected soon after the reappearance and reaching the purely geometric trend, which depends only by the radial velocity, hours after the reappearance. The ordinates are intensity at arbitrary units; the abscissae are the orbital longitudes around Jupiter: 0 means superior conjunction, with angles increasing counter-clockwise.

4. Observations

In 2007 and 2009, we undertook spectroscopic observations to test the hypothesis of condensation of Io's atmosphere on the surface. These observations took advantage of high quality of the Italian 3.6 m telescope TNG (Telescopio Nazionale Galileo) at La Palma Canary Island, equipped with SARG, a high resolution échelle spectrograph with a dispersion of about 0.022 Angstrom/pix, equipped with a Sodium filter in order to avoid order overlapping and simultaneously to use a long slit covering an area of 26.7 x 0.4 arcsec. We took high resolution spectra of Io while entering into Jupiter's shadow and coming out from it, and observations were taken when Earth was at a position that permitted observations of the eclipse itself separated from Jupiter's disk by up to 10 arcsec.

5. Reduction Steps

As we want to study the Na emission from the cloud, we have to remove the sunlight reflected from Io's surface. So, for the purposes of this research, besides the "standard" reduction steps (as bias and flat fielding), the telluric lines removal and the reflected sunlight subtraction must be performed. The conversion between ADUs and kiloRayleighs ($1R = 10^6/4\pi$ $photons$ cm^{-2} sec^{-1} sr^{-1}) has been done using the well known Jupiter's intensity of 5.4 MegaRayleighs/Angstrom. Knowing the g-factor from the γ-factor, under

https://doi.org/10.1017/S1743921310007453 Published online by Cambridge University Press

the assumption of optically thin cloud, it is also possible to get the column density N (expressed in $atoms\ cm^{-2}$) and therefore the amount of sodium present. From Brown & Yung (1976):

$$g = \left[\gamma \pi F_{Sun}(.59)\,\frac{\lambda^2}{c}\right]\frac{\pi e^2}{mc}\,f \qquad (5.1)$$

where g is expressed in $photons\ s^{-1}\ atom^{-1}$; $F_{Sun}(.59)$ is the solar flux at the wavelength λ of the D lines scaled to the Io-Sun distance, expressed in $photons\ cm^{-2}\ sec^{-1}\ \AA^{-1}$, and f is the oscillator strength. The other symbols are standard notation for physical constants. Finally, the intensity is $I = g \cdot N$ and is expressed in kiloRayleighs.

6. Preliminary Results

In Figure 3 we plotted the intensity in Rayleigh as a function of the orbital longitude. The black asterisks are the observed data (referring to the left ordinates), the red diamonds are the γ-factor (referring to the right ordinates), which show the expected trend in the case of a non-condensing exosphere. Observations were taken prior to eclipse in April and May, and after eclipse in June and July.

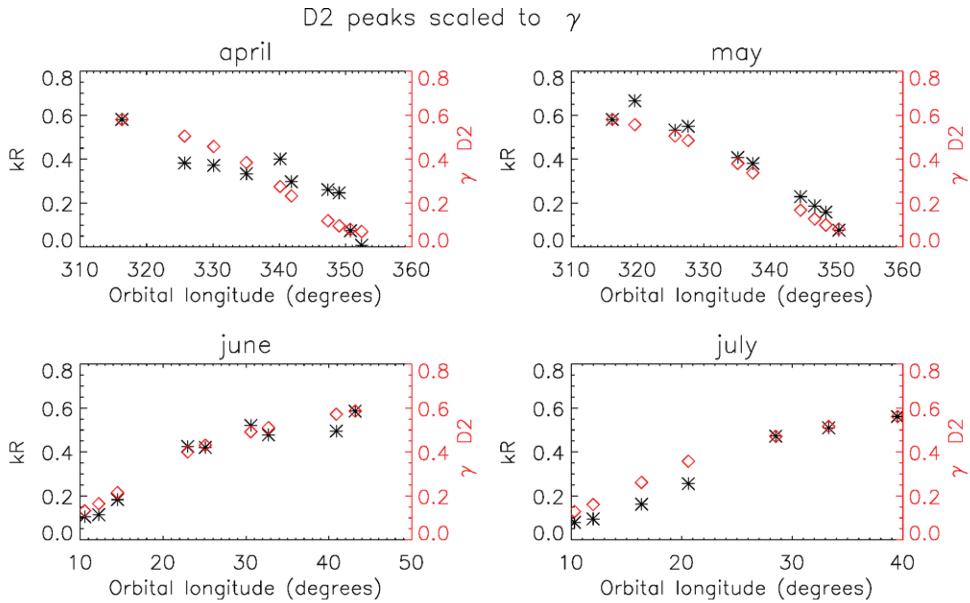

Figure 3. Preliminary results from the 2007 data. Cloud brightness is plotted versus orbital longitude. Red diamonds are the γ-factor in the non-condensing case, black asterisks represent the observed data in kiloRayleighs scaled to the D2 values to show them in the same ordinates range.

The data before eclipse follow the expected trend (in particular May), while data after the eclipse (in particular July) seem to support the condensation hypothesis, with brightness increasing slower than the expected. Further steps are required to understand the outliers (especially in April and June).

https://doi.org/10.1017/S1743921310007453 Published online by Cambridge University Press

References

Brown, R. 1974, *New Scientist*, 64, 484
Brown, R. A. & Yung, Y. L. 1976, in *Jupiter*, p. 1102-1145
Schneider, N. M. & Trauger, J. T. 1995, *ApJ*, 450, 450
Burger, M. H., Schneider, N. M., & Wilson, J. K. 1999, *Geophys. Res. Lett.*, 26, 3333
Schneider, N. M. & Bagenal, F. 2007, in *Io After Galileo*, R. Lopes, ed. Springer/Praxis