Jupiter's X-ray Aurorae

Jupiter's Aurorae

Our ancestors have been marveling at the Earth's aurorae for millennia. In fact, the oldest recording of an auroral sighting is thought to be a 32 000 year old cave painting in Southern France. They could never have imagined that the same phenomenon occurs hundreds of millions of kilometers away on many other planets in the Solar System including Jupiter. It is fitting that the largest planet has the most intense and powerful aurorae, covering almost every waveband. Decametric (wavelengths of tens of meters) and hectometric (wavelengths of hundreds of meters) radio signals were first detected in the 1950s (**Burke et al., 1955**) which led to the discovery of Jupiter's magnetosphere. These signals are emitted through the cyclotron maser instability, a mechanism that makes the energetic electrons that generate the aurorae to spiral due to Jupiter's magnetic field. Ground based telescopes have been surveying the infrared aurorae since the 1980s; they are mostly produced by thermal emissions from H_3^+ in the upper atmosphere. The visible aurora is by far the dimmest of Jupiter's auroral emissions and can only be studied from the night side of the planet as it is easily lost in sunlight. These emissions are due to the de-excitation of H and H_2. Higher energy electronic transitions in H and H_2 are responsible for the UV aurora. Coincidently, the first detections of the UV and X-ray aurorae were both made in 1979 by Voyager 1 and the Einstein Observatory respectively. **Metzger et al., 1983** analysed the X-ray data and were surprised that the X-ray aurorae were not produced by bremsstrahlung radiation as electrons from the radiation belts precipitate into the atmosphere as is the case for the Earth's X-ray aurora. It wasn't until the mid-1990s that the process responsible for those emissions was identified as charge exchange (**Waite et al., 1994; Cravens et al., 1995)**. An electron from a neutral hydrogen atom in Jupiter's atmosphere is captured by a precipitating ion. The highly excited electron will eventually fall to a lower energy state and release a "soft" X-ray photon with energies below 2 keV (wavelengths above 6Å). The exact energy of the photon can determine the ion that it was emitted by. **Branduardi-Raymont et al, 2008** discovered that bremsstrahlung radiation due to electrons slowing down as they precipitate into Jupiter's atmosphere is responsible for a second, more transient, emission of higher energy "hard" X-rays. This emission mostly coincides with the location of the main UV auroral oval (see Figure 1). The X-ray aurora is unique when compared to the aurorae in other wavebands as it is produced by ions and electrons and that the emissions are released by the precipitating particles rather than Jupiter's atmosphere. Around 27% of observations reveal that the X-ray aurorae pulse with a regular beat with periods of tens of minutes **Jackman et al., 2018** but they don't usually pulse simultaneously at both poles. In fact, **Dunn et al., 2017** found that the aurora in both hemispheres can behave very differently to each other.

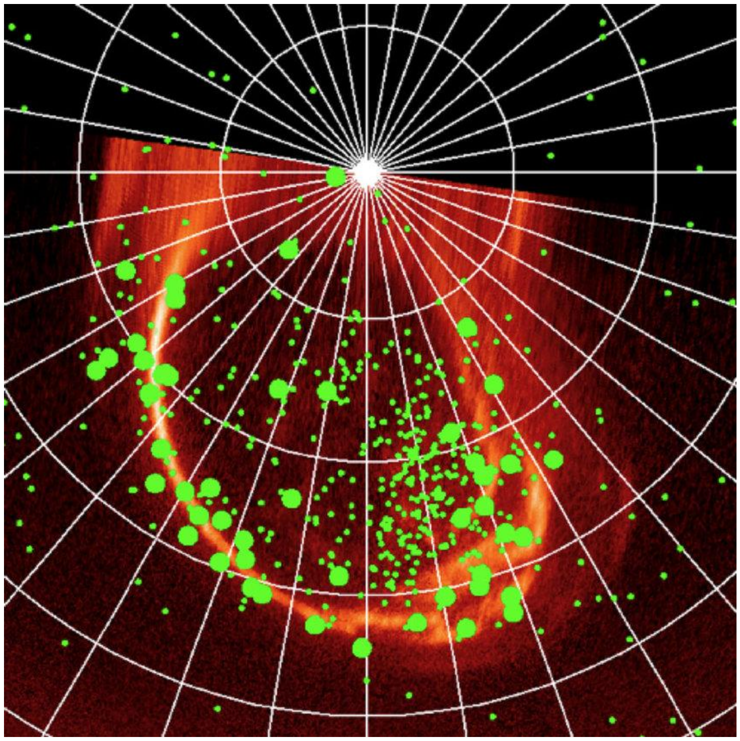

Figure 1 : The Chandra X-ray Observatory and the Hubble Space Telescope were monitoring the X-ray and UV aurorae simultaneously in February 2003. The UV aurora is in orange and overplotted on top are the X-ray photons as green dots. Small green dots represent soft X-rays whereas the large green dots are hard X-rays. Chandra's high spatial resolution means that each X-ray photon can be mapped on Jupiter and therefore tell us where ions and electrons are precipitating into the atmosphere. Magnetospheric mapping tools can then be used to find out where in Jupiter's magnetosphere these ions were accelerated from. Image from ***Branduardi-Raymont et al., 2008.***

Jupiter's Magnetosphere

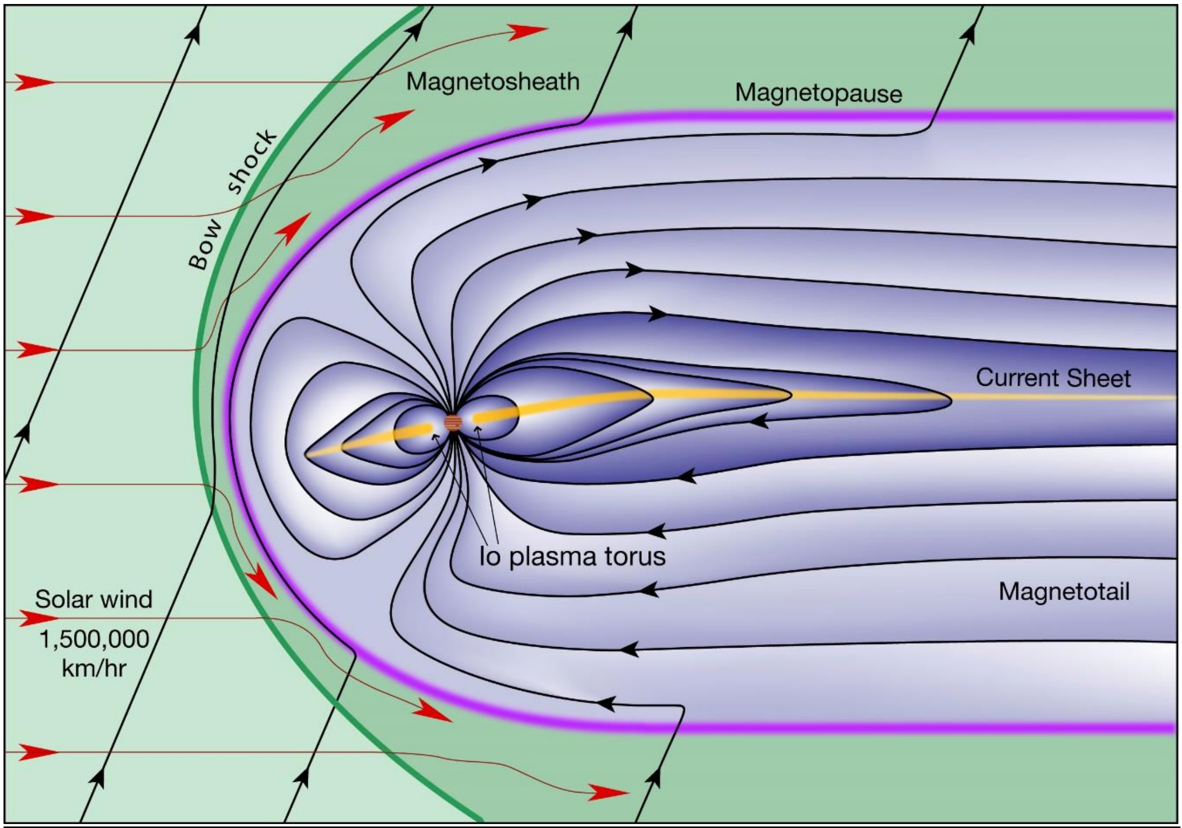

Figure 2 : Schematic of Jupiter's magnetosphere with the Sun on the left. It's often described as the largest structure in the heliosphere and would appear to be as large as the Moon if it was visible from the Earth despite Jupiter being around 2000 times further away to us than our natural satellite.

Cavities in the solar wind are carved out around planets with magnetic fields as the flow of plasma from the Sun is forced to go around this magnetic obstacle. The shape of this cavity, or magnetosphere, is usually described as a tear drop as the solar wind squashes the magnetic field lines in the dayside whilst those in the nightside are stretched far behind the planet to form the magnetotail.

Jupiter has a magnetic moment that is 20 000 times larger than the Earth's. This creates a huge magnetosphere (see Figure 2) that extends out to Saturn's orbit 5 AU away. The location where Jupiter's magnetosphere and the solar wind meet (called the magnetopause) depends on the balance between the solar wind ram pressure and the magnetic and plasma pressure from the magnetosphere itself. If the ram pressure is high, the magnetosphere is compressed, and the magnetopause is about 60 Jupiter radii (R_J) away from the center of the planet. Conversely, the magnetopause is at around 90 R_J when the magnetosphere is expanded. The plasma pressure arises from the plasmadisk which is composed of material ejected by Io's volcanoes. Some 1000 kg of neutral SO_2 molecules are released by the volcanoes every second. The molecules then dissociate and up to half of this material is ionised by collisions and solar radiation. These iogenic (originating from Io) ions are then picked up by Jupiter's magnetic field and are made to accelerate and corotate with the planet. Centrifugal forces flatten this material into a disc which is pushed outwards over a period of around two weeks. The plasmadisk also makes Jupiter's magnetic field lines bend so that the field lines in the inner magnetosphere are no longer dipolar. Observational and theoretical studies suggest these iogenic ions are more likely to precipitate into Jupiter's atmosphere and therefore play a larger role in producing Jupiter's X-ray aurorae than solar wind ions (e.g. **Cravens et al., 2003; Bunce et al., 2004; Elsner et al., 2005; Dunn et al., 2016**). **Wibisono et al., in review** created models to represent the ion populations found in the solar wind and inside the magnetosphere. Results showed that the soft X-ray aurorae are the product of precipitating iogenic ions during a magnetospheric compression event. Furthermore, **Dunn et al., in review** agreed with the outcome when spectra from different datasets were analysed and went further to reveal that the solar wind model seemed a better fit when the magnetosphere is expanded.

XMM-Newton and Juno

The European Space Agency's XMM-Newton X-ray Observatory celebrated twenty years since its launch in December 1999. Its superior spectral resolution is able to accurately record the energies of incoming X-ray photons which is essential to determine the ion that they were emitted by and therefore whether it was iogenic or from the solar wind. Furthermore, it has a large effective area which means that its mirrors are able to collect a high number of X-ray photons at different energies. This ensures that XMM-Newton can capture as many of the low number of X-ray photons from Jupiter as possible.

XMM-Newton is typically used by astrophysicists to observe some of the most exotic and energetic objects in the faraway universe, such as pulsars, black holes and galaxy clusters. However, it has on a few occasions been used to study X-ray emissions from some of our nearest neighbours like Mars, Jupiter and Saturn. X-rays from Mars and Saturn are the result of elastic and fluorescent scattering of solar X-rays from their atmospheres. It first turned its attention to the King of the Planets in April 2003 and has since then obtained 1.5 million seconds of data of the jovian aurorae over twenty observations.

The Juno spacecraft began its five year journey to Jupiter in 2011. Since its succesful orbital insertion around the giant planet, its suite of instruments has already helped planetary scientists to learn more about Jupiter's gravity and magnetic fields, as well as the dynamics and composition of its atmosphere. This has brought us closer to revealing how Jupiter formed and evolved over the last 4 billion years or so. In-situ measurements of Jupiter's magnetosphere can also be used in conjunction with data from XMM-Newton and other ground based and Earth-orbiting observatories to tell us more about what drives Jupiter's aurorae.

Compressed Magnetosphere

One of the first Jupiter XMM-Newton observations since Juno arrived at Jupiter occurred on 19 June 2017. Data were collected by XMM-Newton for almost 2.5 jovian rotations, or ~23 hours, when the planet was at a distance of 5.1 AU from the Earth. Juno was located in the dawn flank of Jupiter's magnetosphere at a distance of ~110 R_J and its position was close to where the magnetopause is expected to be if the magnetosphere was compressed by a strong gust of solar wind, as determined by the model described in **Joy et al., 2002**.

The Jovian Auroral Distributions Experiment (JADE) is one of the particle detectors on Juno that quantify the energy, velocity and angular distributions of ions and electrons (**McComas et al., 2017**). Information about Juno's position and data from this instrument can be used to determine whether Jupiter's magnetosphere was compressed. Figure 3 shows JADE's measurements of the ion energy per charge (panel A) and electron energy (panel B) before and during the XMM-Newton observation (marked by the dashed orange box). There are abrupt changes in both at point 1 that correspond to the magnetopause passing over Juno as the magnetosphere is being compressed by the solar wind. At this point, Juno finds itself in Jupiter's magnetosheath (a region of shocked solar wind ions that is upstream of the magnetopause) rather than in its magnetosphere. The magnetopause crossed Juno again at point 2 hinting that the magnetosphere was starting to expand.

The brightness and morphology of Jupiter's northern UV aurora, as observed by the Hubble Space Telescope 14 hours before XMM-Newton's campaign, and the prediction of a solar wind compression arriving at Jupiter on 19 June by the **Tao et al., 2005** solar wind propagation model support our inference that the magnetosphere was compressed.

Also marked in Figure 3 are the intervals when the X-ray aurorae were pulsating (see the "Quasi-periodic Pulsations" section).

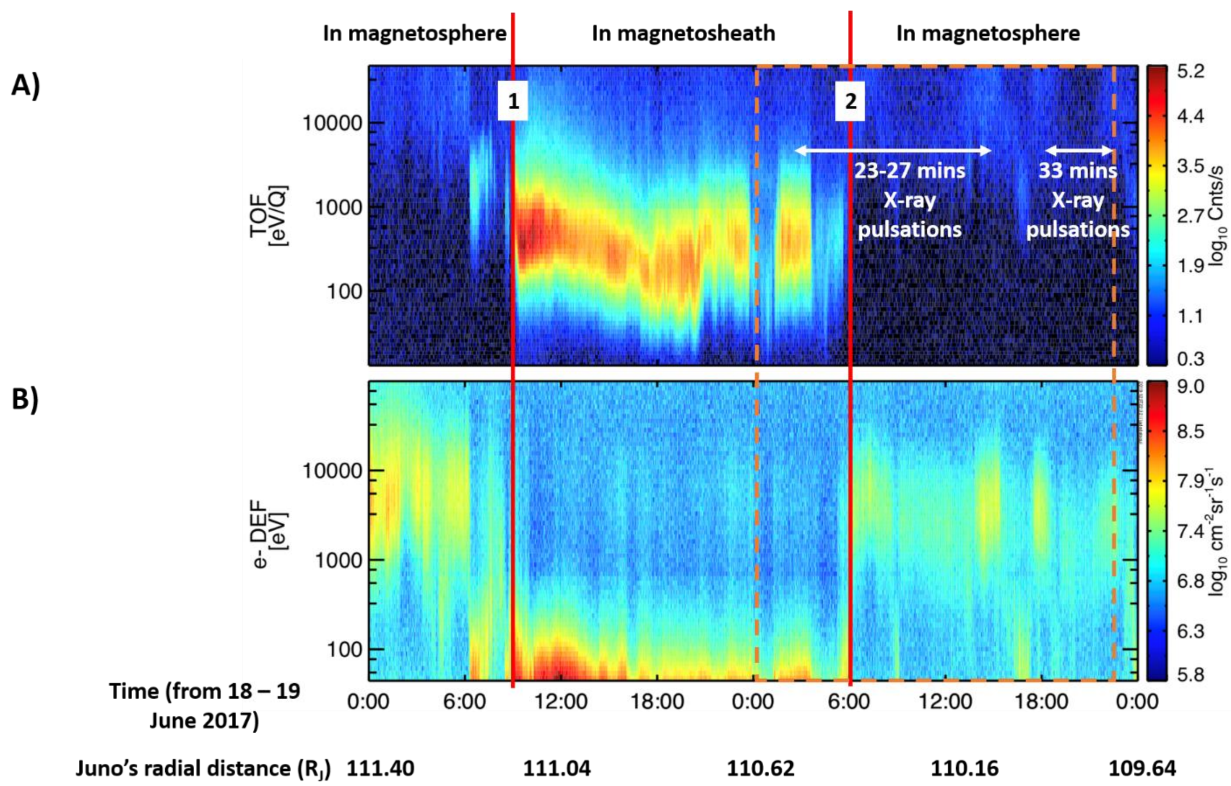

Figure 3: Panel A gives the ion energy per charge while Panel B gives the electron energy distribution. The colour bars represent the count rates of the ions and electrons. The red vertical

lines mark the times when the magnetopause moved across Juno bringing the spacecraft inside or outside of the magnetosphere. XMM-Newton's observation of Jupiter occurred during the orange dashed box. The X-ray aurorae were pulsating over the white horizontal lines. Modified from ***Wibisono et al., in review****.*

<u>The XMM-Newton Observation</u>

Figure 4 is the XMM-Newton image of Jupiter from our June 2017 observation. Areas in white and yellow have high number of X-ray photon counts, whereas blues and blacks have low counts. Jupiter's disk is depicted by the green circle, the equatorial region is in the pink rectangle and the northern and southern aurorae are in the yellow and white ellipses respectively. Jupiter's atmosphere is known to be a good mirror for solar X-rays due to elastic collisions and, to a smaller degree, by fluorescent emissions from hydrocarbons in Jupiter's atmosphere **(Maurellis et al., 2000, Cravens and Maurellis, 2001)**. There is a small amount of reflected solar X-rays from the disk, hence the red pixels inside the green circle.

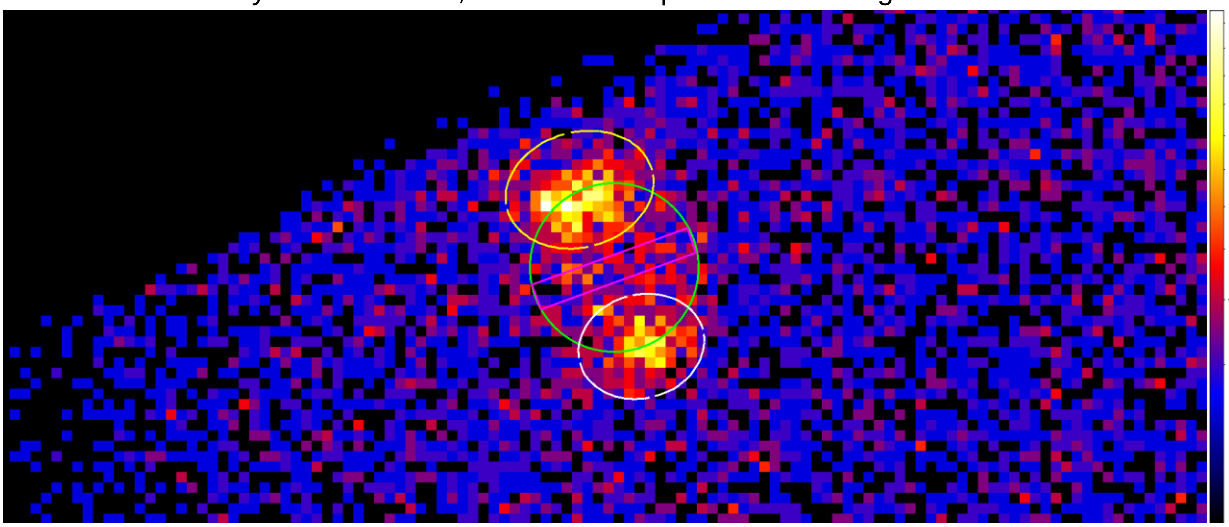

Figure 4: XMM-Newton image of Jupiter and its X-ray aurorae. The green circle marks the planet's disk, the pink rectangle shows Jupiter's equatorial region and the yellow and white ellipses are the auroral emissions. The colour bar scale indicates the number of X-ray photon counts. The disk shows some scattered and reflected solar X-rays.

The aurorae are fixed on Jupiter's frame so that from our vantage point we can see the aurorae come in and out of view as the planet rotates. We can observe the northern aurora when the Central Meridian Longitude (CML – Jupiter's line of longitude pointed towards an observer at Earth) is between 155 - 190° and the southern aurora when the CML is between 0 - 75° (using the System 3 coordinate system) as can be seen in the lightcurve in Figure 5. We can see that the northern aurora (in blue) was visible twice and the southern aurora (in orange) three times during this observation. The northern aurora is generally brighter than its southern counterpart, which was the case for this observation, although the southern aurora did release a couple of bright flares at ~21:00 UT. The reason for the asymmetrical brightness is mostly likely due to more favourable viewing angles for the north and/or due to differences in the local conditions (e.g. the magnetic field is stronger at the north pole).

We can also see that within some of the viewing periods (e.g. when the northern aurora is first visible between 03:00 - 06:00 UT) the aurorae have regular quasi-periodic pulsations – the peaks are evenly spread out but don't always reach the same number of X-ray photons counts.

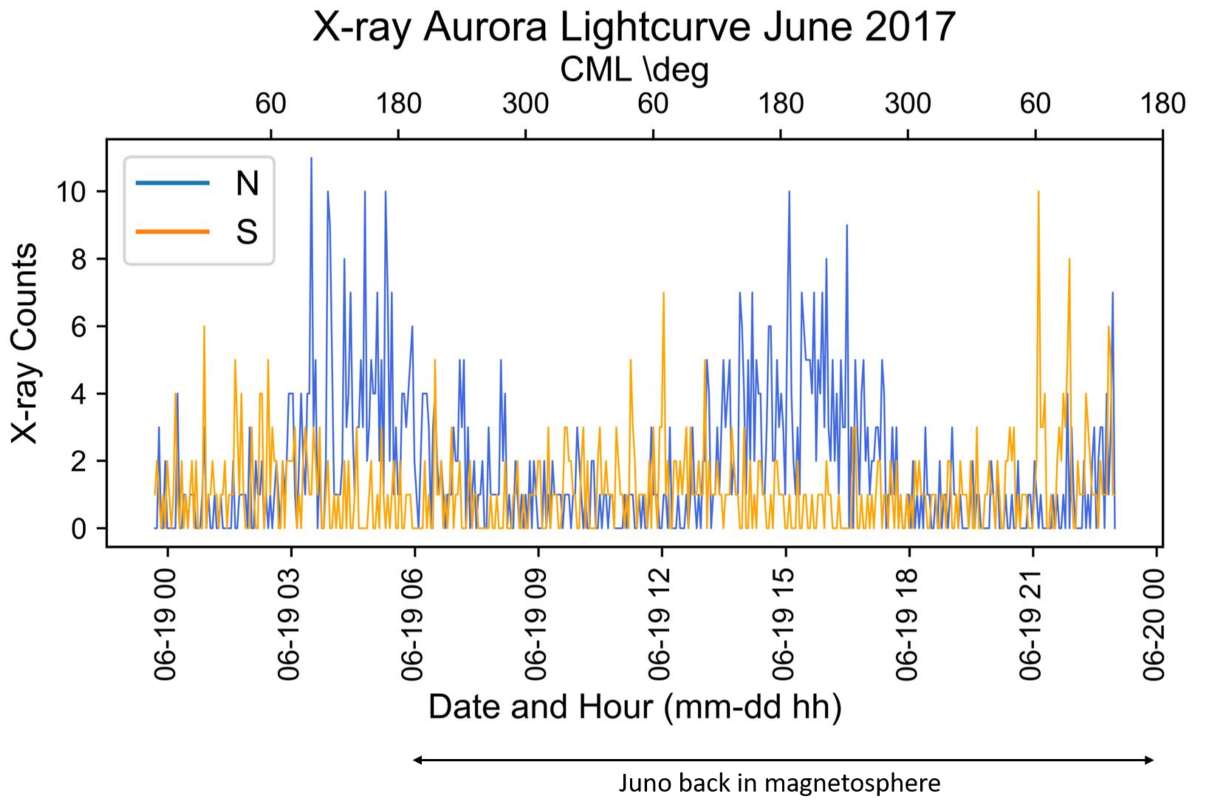

Figure 5: XMM-Newton lightcurve of the northern (in blue) and southern (in orange) X-ray aurorae. The southern aurora emitted bright flares at 21:00 UT which rivalled the brightness of the northern aurora. The aurorae exhibited regular pulsations during part of this observation. Juno was back inside the magnetosphere for most of this observation. From ***Wibisono et al., in review****.*

Quasi-Periodic Pulsations

We applied a discrete wavelet transform on the lightcurve in order to investigate if and when these pulsations start and stop. A wavelet is a rapidly decaying wave-like oscillation that only exists for a certain duration. There are several different types of wavelets, each with their own unique shape. A wavelet with a very small width is moved across the lightcurve to pick out the highest frequencies and the times when they occur with very good time resolution. The wavelet is then widened and moved across the lightcurve again to find the lower frequencies. However, the time resolution is now not as good and so we are less certain about when those lower frequencies occur. This process is repeated with wider wavelets to find lower frequencies with lower time resolution until the width of the wavelet is equal to the width of the whole lightcurve. The results are presented in a power spectral density (PSD) plot such as in Figure 6. The red regions on the PSDs indicate when the aurorae are in view. Here, dark red shows when there are strong pulsations and dark blue when no regular periodicities were found in the lightcurve.

There is a very strong pulsation with a period of 20 - 40 minutes in the northern aurora starting at around 03:00 UT and ending with a lower power at 06:00 UT. The period of the pulsations seems to lengthen during this time as indicated in panel A of Figure 6. A similar period occurs when the northern aurora comes back into view at 12:00 UT but stops part-way through the rotation at 15:30 UT. There is a hint of a 20 - 30 minute pulsation in the southern aurora (Figure 6, panel B) between 09:00 - 12:00 UT which then lengthens to 45 minutes and increases in power from 20:00 UT until the observation's end.

Knowing when the aurorae were regularly pulsating, a Fast Fourier Transform (FFT) was run on those specific time intervals to determine more accurate periods of those pulsations. The lightcurve can be considered as a the superposition of many sine curves with different amplitudes and frequencies. The FFT can find the frequencies of all of the component sine waves and the results shown in a PSD plot, such as those in Figure 7. These are presented in the order that the aurorae were in view. The southern aurora was the first to be visible, however, there were no statistically significant regular pulsations during this time. The statistical significance was tested by generating 10 000 simulated lightcurves using Monte Carlo methods and determining how often a periodicity of the observed power would be randomly generated. The first time that the northern aurora was in view (PSD panel A) shows peaks at ~23 and ~27 minutes that reach the 90th and 99th percentile marks respectively. NASA's Chandra X-ray Observatory was also surveying Jupiter during the first five hours of this viewing window and analysis of its lightcurve also showed regular pulsations of ~26 minutes (**Weigt et al., 2020**) which supports our findings. The second rotation of the southern aurora (PSD B) has one large peak at ~23 minutes which was also present later in the northern aurora (PSD C). However, the period found in PSD D was longer, at ~33 minutes. Pulsation periods of a similar duration have previously been observed (e.g. **Dunn et al., 2016**), however, the aurorae at the two hemispheres have never been seen to pulsate regularly with the same periods over multiple Jupiter rotations before.

A potential driver for these quasi-periodic pulsations are ultra low frequency (ULF) waves which are known to have periods of tens of minutes at Jupiter. A magnetic field line in the outer dayside magnetosphere is perturbed by a solar wind compression which sets a standing wave to travel along this field line. This standing wave can couple with other magnetohydrodynamic waves to accelerate ions and electrons into the atmosphere to produce the aurorae. The period of this standing wave depends on its speed (which depends on the density of the medium that it is travelling through – so its speed is reduced when it is moving through the plasmadisk) and the length of the magnetic field line. Therefore, this could explain why we see pulsations with different periods throughout the observation as different magnetic field lines would have been disturbed due to the changing size of the magnetosphere. This would also mean that between 03:00 – 15:30 UT, the aurorae and their driver in the magnetosphere were oscillating with the same regular period for more than one Jupiter rotation to give the recurring 23-minute period. The simultaneous pulsations at both poles also suggest that the northern and southern X-ray aurorae can share the same driver and that they can pulse in time as well as pulse independently of one another (e.g. **Dunn et al., 2017**).

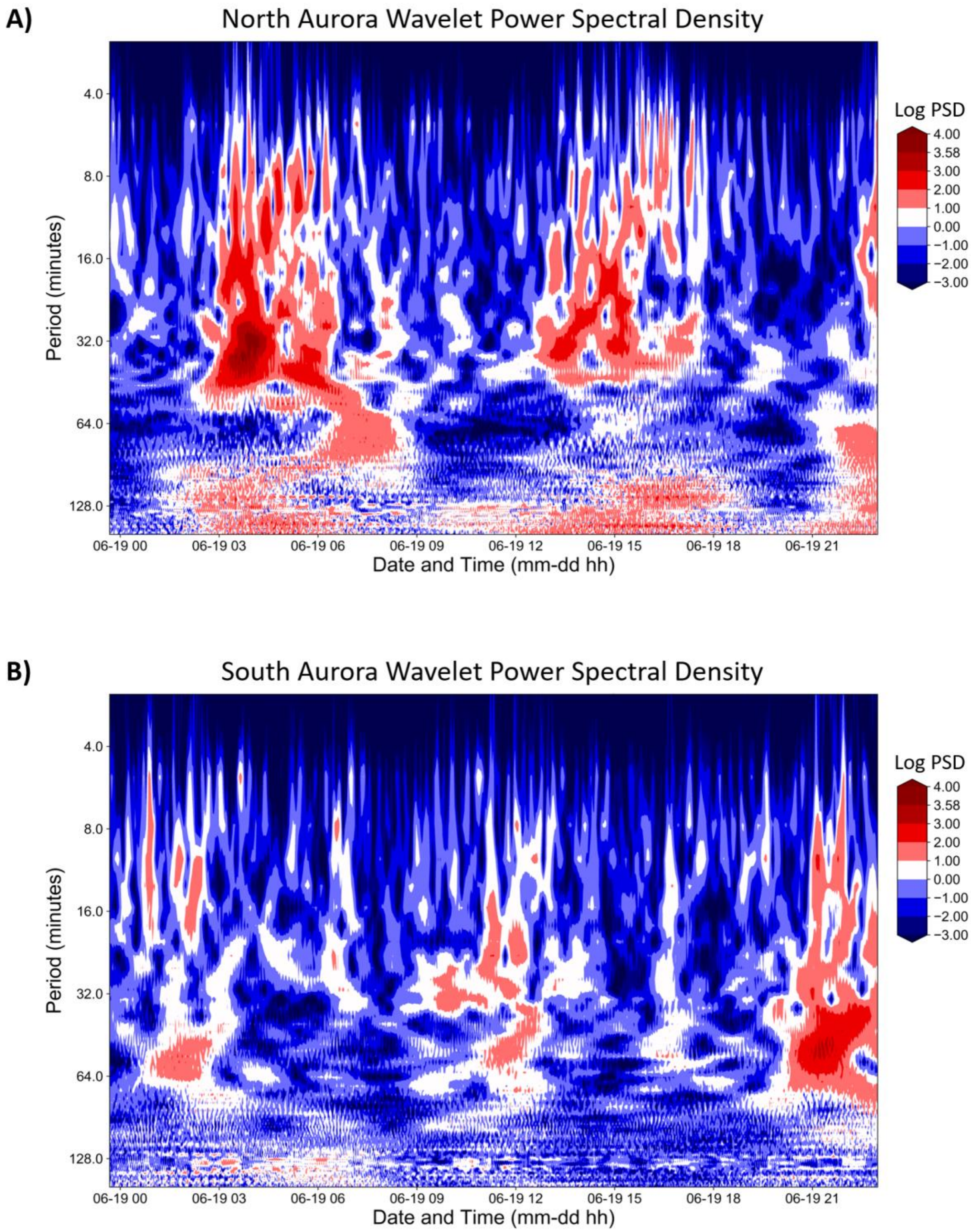

*Figure 6: The PSD plots of the northern (panel A) and southern (panel B) aurorae after a discrete wavelet transform was applied on the lightcurve. The colour bar shows the PSD on a log scale with dark red having the highest power and dark blue the lowest power. From **Wibisono et al., in review**.*

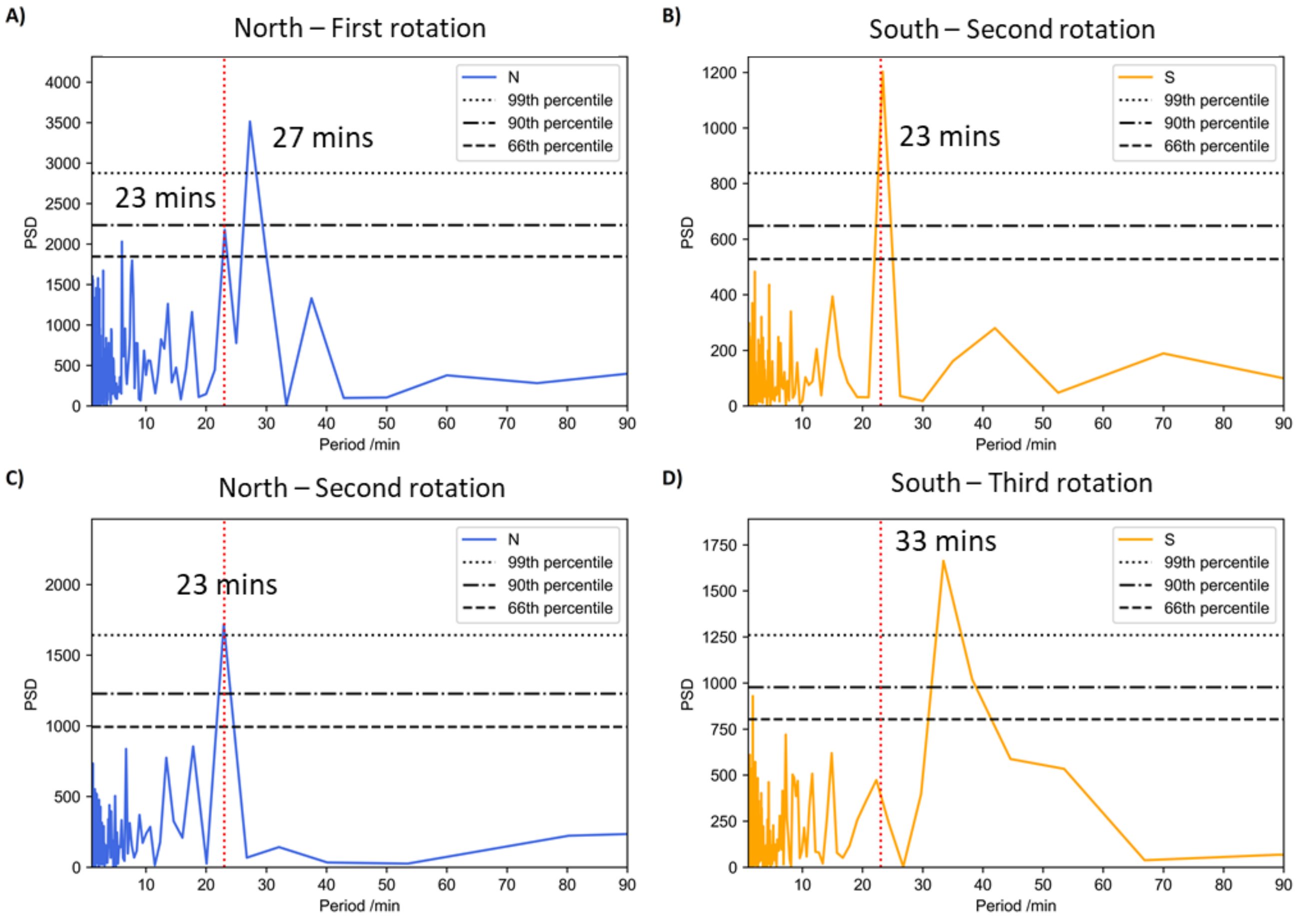

Figure 7: The PSD plots after the FFT was applied on the time intervals when regular pulsations occurred. PSDs A and C are for the entire first rotation and start of the second rotation into view of the northern aurora respectively. PSDs B and D are for the beginning of the second and entire third rotation of the southern aurora respectively. The dashed, dashed-dot and dotted black lines mark the 66th, 90th and 99th percentiles. The vertical red dashed lines show when the period is equal to 23 minutes. Modified from ***Wibisono et al., in review****.*

Conclusions

The combination of X-ray observations from Earth by flagship missions such as ESA's XMM-Newton observatory, with NASA's paradigm-shifting Juno spacecraft, is providing a revolution in our understanding of how Jupiter produces its dynamic and enigmatic auroral emissions.

XMM-Newton's observation of Jupiter on 19 June 2017 coincided with a clear magnetospheric compression event as determined by Juno's JADE instrument, HST's observation of the UV aurora and the Tao solar wind propagation model. Shortly after the magnetosphere was compressed, the northern and southern X-ray aurorae exhibited regular pulsations of 23 – 27 minutes over a duration of more than 12.5 hours. This is the first time that the two have been observed to synchronously pulse with the same period over multiple Jupiter rotations and hints that the X-ray aurorae from both hemispheres could share the same driver. The southern aurora continued to release bright flares and pulsed at a longer period of 33 minutes.

Juno will be moving into the dusk side of Jupiter's magnetosphere over the next year or so before the expected end of its mission in July 2021. A number of observations of the X-ray aurorae by XMM-Newton and Chandra are planned to occur during this time and will mark the first time that contemporanous in-situ and remote X-ray observations have happened in this part of Jupiter's magnetosphere. Using these data and those that we have been collecting since 2016 will hopefully finally reveal whether the mechanisms that produce Jupiter's X-ray aurorae happen locally or globally.

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