Stellar Flares of the Hot Jupiter Host Star HD 189733 A: Testing for a Possible Planetary Influence

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ABSTRACT

Stellar flares are energetic eruptions that occur due to spontaneous rearrangements of stellar magnetic field lines. The question of whether close-in planets can influence or trigger stellar flares has been investigated for several years. Here we study the binary star system HD 189733 which consists of a K dwarf and an M dwarf. There is a Hot Jupiter orbiting the K dwarf with an orbital period of approximately 2.2 days. In 2009 and 2011, X-ray observations were used to discover stellar flares on the K dwarf HD 189733 A occurring at the same point in the orbital period of this Hot Jupiter in both years (Pilletteri et al., 2011). We sought to take more data on this system and discover whether or not there was a firm correlation between the orbit of this planet and the stellar flares on HD 189733 A. We did this by using echelle spectra and observing the change in depth of the H- alpha lines over time, which would indicate whether or not stellar flares were occurring. By studying the change in the depth of the H-alpha line versus the phase of the orbital period of the planet, we created an H-alpha curve that shows the flare activity on HD 189733 A for the nights when our data was taken. Our analysis shows a complete lack of flares of the magnitude Pilletteri et al. (2011) observed, not only in the predicted portion of the orbital period, but also in the entire data set. This suggests that such flares are an extraordinary occurrence for this star and likely do not occur regularly during every orbital period of the Hot Jupiter.

1. Introduction

Stellar flares are a well-documented occurrence in sun-like stars. A stellar flare is a sudden and drastic increase in brightness in a small region of a star. It is thought that stellar flares are caused by magnetic reconnection of the stellar magnetic field lines, which heats the plasma in the corona and chromosphere of the star. Stellar flares produce a large quantity of emission in the H-alpha and Sodium-D lines. These lines, particularly H-alpha, have long been used to observe stellar flares, as they are well-defined and easy to observe. More recently, stellar flares have been observed in X-ray and ultraviolet bands. These methods are efficient, but are oftentimes constrained by the logistical difficulties of observing in these bands because the observations are taken with space telescopes.

One star in which stellar flares have been observed is HD 189733 A. HD 189733 A is a K-type star 19.3 pc away from the sun. It is part of a binary star system, with the secondary star being an M-dwarf located about 3200 AU away from HD 189733 A. As discovered by Bouchy et al. (2005), there is a Hot Jupiter (HD 189733 b) orbiting HD 189733 A at a distance of 0.031 AU with a period of 2.219 days. This is interesting because Hot Jupiters have been suspected to have significant tidal and magnetic interactions with their host stars when at a distance of less than 0.1 AU (Cuntz et al. 2000). Conclusive observational evidence, however, is still missing.

In 2009 and 2011, Pillitteri et al. (2011) detected stellar flares on HD 189733 A using X-ray observations. Both of these flares, though years apart, occurred at approximately the same phase in the orbital period of HD 189733 b: 0.54 in 2009 and 0.52 in 2011 (with the orbital period scaled to one). It was hypothesized that the reason for these events was an active region on the surface of HD 189733 A that has many flares due to the magnetic activity triggered by its interactions with HD 189733 b, and that this region was primarily visible at about 0.5 of the orbital period of the planet.

2. Methods

2.1. Data Reduction

The spectra studied in this work were taken at the McDonald Observatory in Texas on the Sandiford echelle spectrograph. Data was taken over the course of 14 contiguous nights from July 21, 2012 until August 3, 2012. Three of these nights (July 26, July 28, and August 3) were clouded out, leaving usable data from 11 of these nights. The data was in the form of echelle spectra, giving multiple orders of spectral lines to observe.

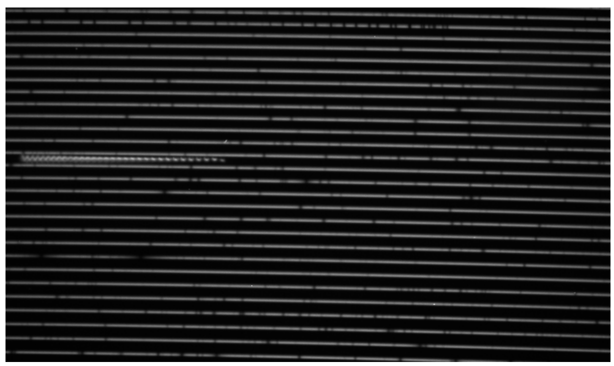

Fig. 1.— The echelle spectrum before data reduction.

Once the data was obtained, basic cosmics removal was performed. A bias frame was then obtained by taking a zero second exposure and then was subtracted from the data to eliminate the electronic noise present in the CCD.

Next, a curious complication was discovered. Due to an imperfection in the spectrograph, an elliptical area of the echelle spectra was blurry. Inconveniently, this area happened to fall right on the portion of the spectra that contained the H-alpha line, so it desperately had to be adjusted for, given that this work was based on the analysis of the H-alpha line. It was postulated that the blurry area was caused by a defect in the spectrograph which caused light from the actual spectra to bleed into the dark parts of the image, creating a blended grey area. To correct for this, IRAF was used to change the

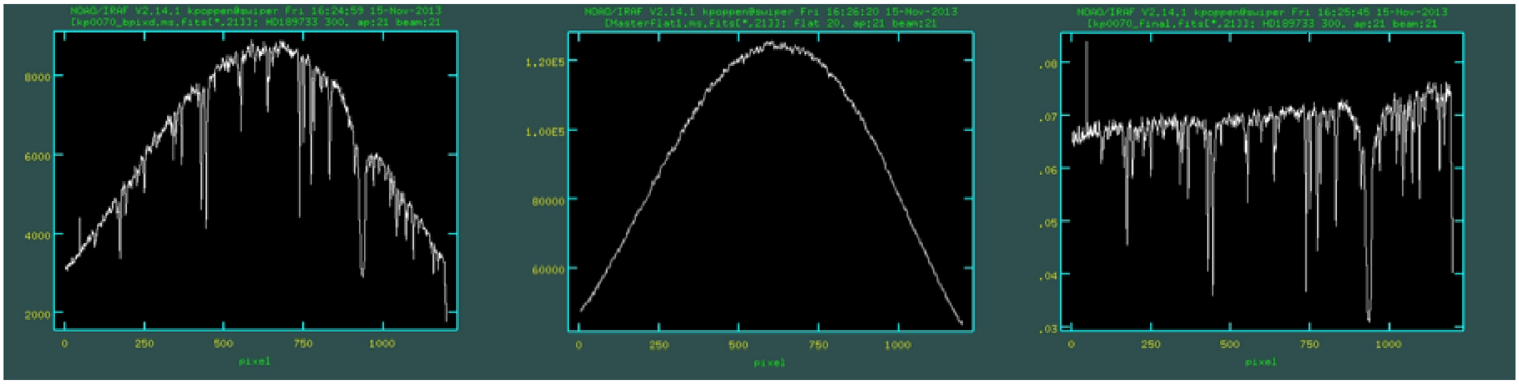

Fig. 2.— The flat fielding sequence. The left panel shows an order of the echelle spectrum before flat fielding. The central panel shows the flat which was applied to the spectrum. The right panel shows this order after the flat field has been applied.

aperture size of the affected orders. In this way, the light that had seeped out of the spectra was returned to the usable data and analysis could continue. This process was checked for effectiveness by examining the affected and adjacent spectral orders and comparing the absorption features in these orders to ensure that no one order had lines that were too strong while causing others to be weaker. It was found that this process was effective and had no adverse effects on the data. This process was done manually for one spectrum in every individual night and then applied to all of the other spectra in that night using an automated code. The order containing the H-alpha line was then pulled out from each full spectra. That order was then divided by the flat for that order to correct for the non-uniform sensitivity of the pixels across the CCD. The units were then converted from pixels to Angstroms for the x-axis.

At this point, it was apparent that there were still a few stray cosmic rays in the data. To adjust for this, a script was written that would go through each spectra and remove any data points that had values much higher than the median value of the neighboring data points. In order to this, the average scatter of a good spectrum (one without too much noise or many cosmics) was estimated. This was found to be about 0.01. Then, a script

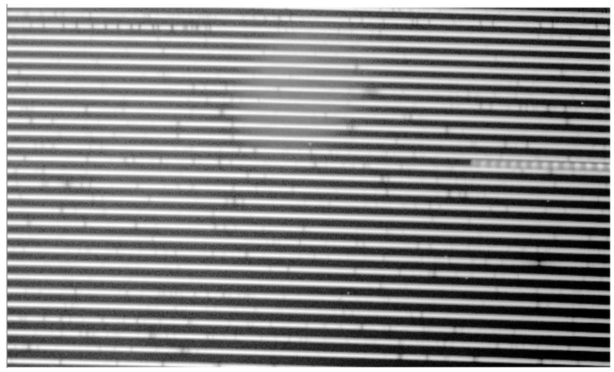

Fig. 3.— The blurry region of the spectrum.

was written that removed any data points that were more than four times that scatter. (This did not affect the spectral lines because only absorption lines were being studied. These lines had negative values, and only points that had very large positive values were removed.) Once this was achieved, the "bad spectra" were then eliminated. Bad spectra were defined as anything that was excessively noisy. To perform this elimination, an area of the spectra with no absorption or emission lines was chosen and the average scatter was estimated for this area. The area that was chosen for this purpose was from 6615 Å to 6620 Å on the x-axis. The average scatter was taken to be about 0.01 for this section for each night. All spectra that had a standard deviation of greater than 0.02 (two times the estimated scatter) in that section were then removed. The spectra (which now contained only the H-alpha line order) were then all normalized to a continuum level of one so that comparative analysis would be possible.

2.2. Methods of Analysis

At this point, it was possible to begin analyzing the reduced data. Stellar flares would be detected by perceiving a change in the depth of the H-alpha line. It was decided that the best way to measure the change in the H-alpha line would be to find the equivalent

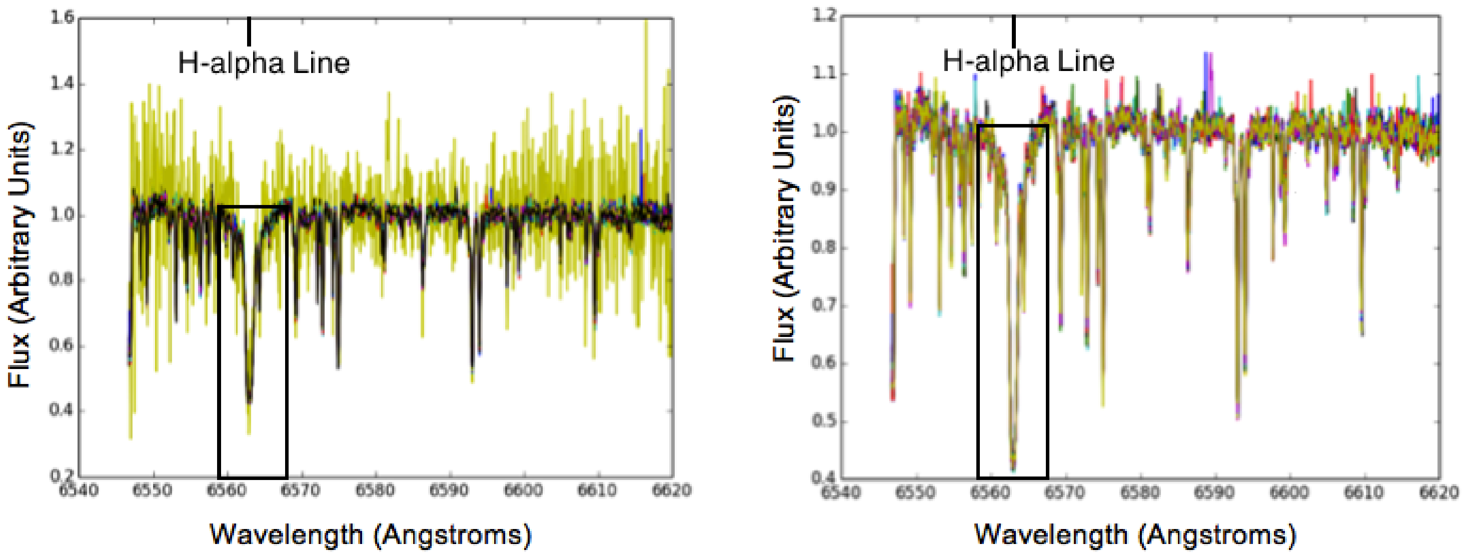

Fig. 4.— Elimination of “bad spectra.” The left panel shows an initial overlay of all the spectra for one night. The right panel shows the overlay with all of the ”bad spectra” removed. The H-alpha line is marked on these plots. The black rectangle denotes the edges of the H-alpha line as used to calculate the equivalent width.

width of the H-alpha line of every spectrum and plot the equivalent width measurements of each night over time. The equivalent width is the width of a rectangle with the same height as a spectral line and containing the same area. The edge points of the H-alpha line were declared to be 6558 Å and 6568 Å and the height was already set at 1 because of the normalization of the spectra. The area of the H-alpha line was then found by subtracting the flux values (the y-axis values) from 1, the height. Simple arithmetic gives the equation that the area of the rectangle is equal to the base of the rectangle times the height. Because the height was 1 in this case, the area was simply equal to the base, which was the equivalent width. This led to graphs of the equivalent width versus time (H-alpha curves) where a flare was indicated by a large dip in the line. For the sake of convention, the negative of the equivalent width was plotted, so that flares would be indicated by a large spike in the H-alpha curve.

When this was done, it was noticed that some of the H-alpha curves were unexpected shapes. It was discovered that this was due to the airmass on the nights when observing took place. Additionally, the airmass was causing water lines in the region of interest which could interfere with the measurements. This was corrected for using the equation:

$$I_{observed} = I_{star} \times e^{k \times airmass} \tag{1}$$

The airmass values were known from the telescope; $I_{observed}$ was the observed intensity as it was recorded in the data; and I_{star} was the true intensity of the star, which was what was being calculated. The k value needed to be found before we could use this equation. To find k, a night that could be seen by eye to have low variability and very few bad spectra was selected: August 2nd. The k value was then found for this night by testing an array of candidate values to discover which value would result in the lowest standard deviation for the H-alpha curve. These values ranged between 0 and 1 in increments of 0.001. The k value was thus found to be $k = 0.011$. This value was then used for all of the nights in the data set. The airmass was then removed from the H-alpha curves.

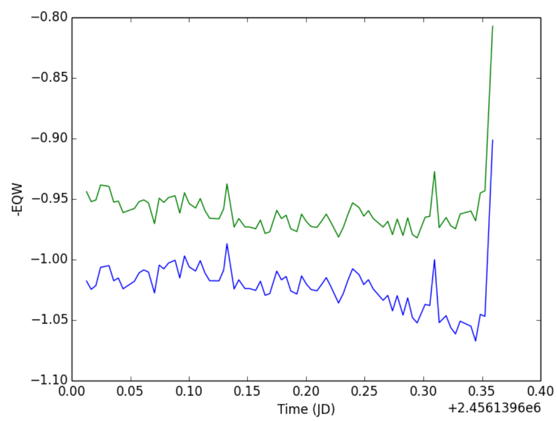

Fig. 5.— Airmass effects. The blue line shows the uncorrected H-alpha curve and the green line shows the curve with the airmass removed.

The y-axis shows the change in the depth of the H-alpha line scaled to 1 and the x-axis shows time. Error bars were then estimated. This was done by finding the standard deviation of each spectrum in a region without any strong absorption or emission features, multiplying that value by 10 to account for the fact that the equivalent width was calculated using an area containing 100 pixels, and then applying the error estimated for each spectra to the corresponding point in the H-alpha curve.

3. Results

When all of the nights are plotted on the same graph against time in days, an interesting sinusoidal period emerges. Looking at the plot, there is an upward and downward modulation with a period of about 11 days. Our measurements therefore confirm previous observations which showed that HD 189733 A has a rotation period of about 11 days (Bouchy et al., 2005). This is suspected to create this kind of sinusoidal H-alpha curve because one side of the star is predicted to always be more active than the other, so when the more active region is facing the earth, the H-alpha emission is greater, creating a sinusoidal shape in the H-alpha curve.

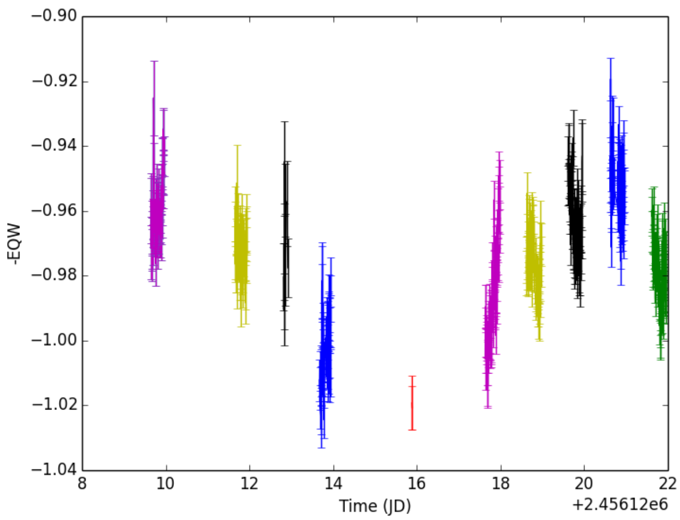

Fig. 6.— The plot showing the sinusoidal period of the H-alpha activity of HD 189733 A.

The idea of this project was to study where flares were occurring in relation to the orbit of the planet HD 189733 b, so the units of time were converted from Julian dates to phases of the orbit of this planet. The length of the orbital period was known, as was the Julian date of the midpoint of a recent transit of the planet. Using this transit as the zero point of every period, the H-alpha curves were plotted along this period. This was done by subtracting the known Julian date of the middle of the transit from the observed Julian date for every spectrum, which correlated with an equivalent width data point, and then dividing this difference by the orbital period of the planet. The remainder of this division was then the x-axis value for that point. The H-alpha curves were then plotted with change in equivalent width on the y-axis and the orbital period on the x-axis running from 0 to 2.219 (the length of the orbital period in days). The x-axis was then normalized to one, so that the portion of the period could easily be detected.

When all of the nights were plotted in this form, as in Figure 7, flares should have been obviously shown by a large spike in the measurements of the equivalent width. From a cursory glance at the individual nights H-alpha plots, it seemed unlikely that there were any large flares. When all of these nights were plotted together on one graph, the H-alpha activity was shown in relation to the period of the orbit of the planet. From simply looking at this graph, it can be seen that there are no clear spikes in the H-alpha activity. Some of the values are greater than others, but this is most likely due to the overall increased activity due to one side of the star being more active than the other, as mentioned above.

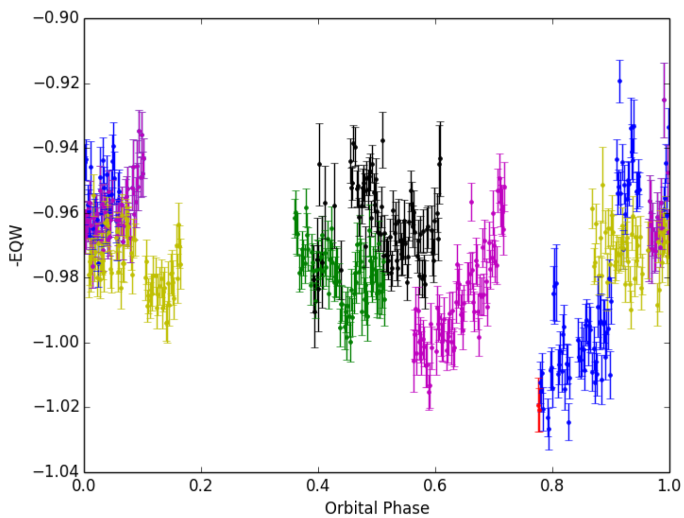

Fig. 7.— The plot of the final data, showing the H-alpha curves for each night plotted over time. The lack of any distinct large spikes suggests a lack of strong flares.

4. Discussion and Conclusion

Pillitteri et al. (2011) found that the stellar flares they detected increased from approximately 100 cts/ks to approximately 200 cts/ks. These observations were made in X-rays, however, so the numbers and proportions do not automatically translate directly to what one should see in an H-alpha curve for a flare of the same magnitude. In order to compare X-ray curves and H-alpha curves, Figure 8 was used. These graphs come from Fuhrmeister et al. (2011), and show observations of Proxima Centauri, which is also a cool star with a magnetically active chromosphere and corona and can be assumed to have similar emission ratios in H-alpha and X-rays as HD 189733 A.

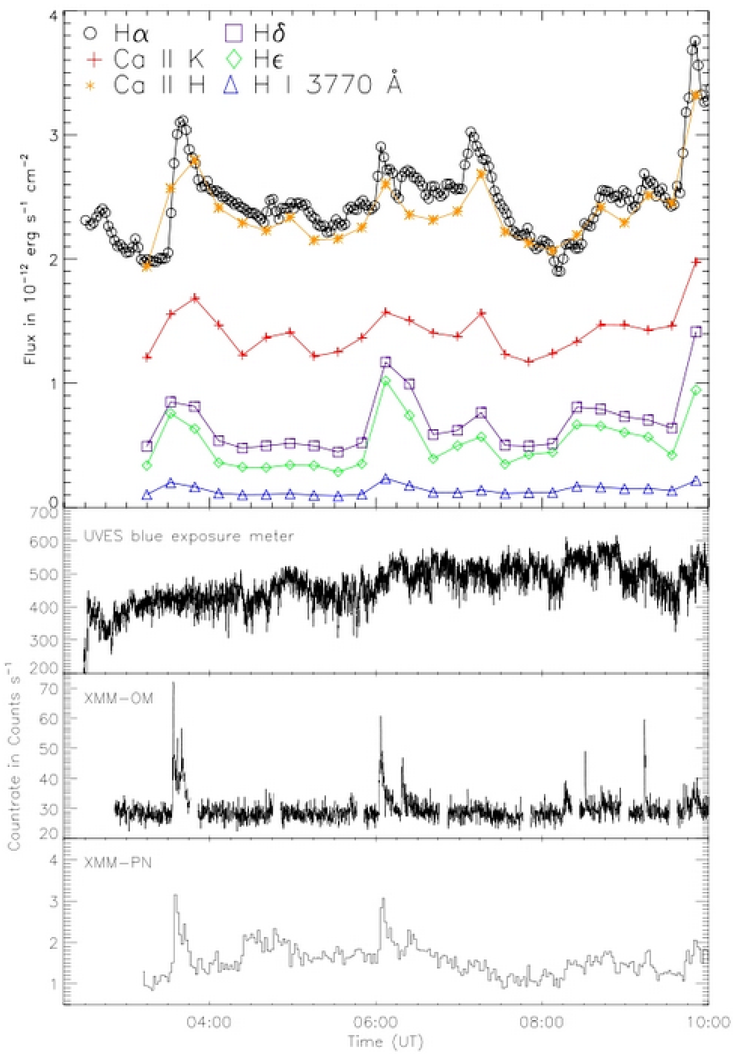

Fig. 8.— Observations of Proxima Centauri from Fuhrmeister et al. (2011), showing comparisons between X-ray and H-alpha observations.

Looking at Figure 8, the bottommost plot shows X-ray observations during a stellar flare. The first large spike that can be seen just before 4:00 UT indicates a stellar flare. This flare goes from about 1 count/second to about 3 counts/second with a scatter of about 0.5. The uppermost plot shows a number of different observation types, H-alpha emission among them, indicated by the open black circles. This data was taken simultaneously with the X-ray data, so the same flare can be observed just before 4:00. In the H-alpha emission line, this spike goes from a flux of approximately 2 $\times 10^{-12} ergs^{-1} cm^{-2}$ to approximately 3 $\times 10^{-12} ergs^{-1} cm^{-2}$ with a scatter of about 0.25. By comparing these two spikes in the X-ray and H-alpha data, a conversion factor can be obtained. The spike observed by Pillitteri et al. more than doubles in size, increasing from approximately 100 cts/ks to approximately 225 cts/ks with a scatter of about 20, so a corresponding H-alpha spike with an error of approximately 0.1, as the data being analyzed here, would have to at least double in size to be close to the same magnitude of the flares that Pillitteri et al. observed.

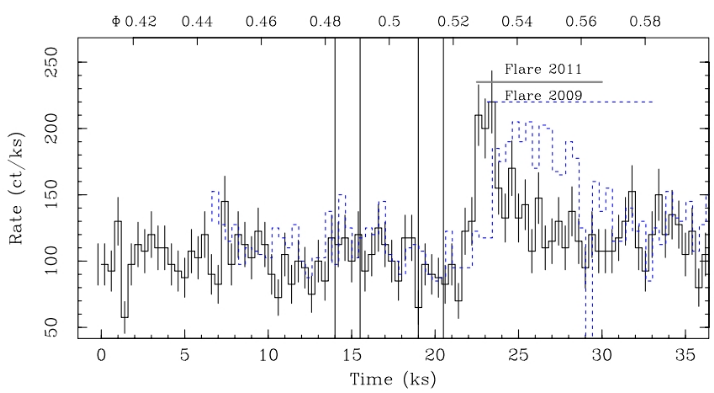

Fig. 9.— The original plot of Pillitteri et al. showing large flare spikes at around 0.5.

Observing Figure 7, it can be noted that there are no flares of anywhere near this size. The entire graph spans a range of about 0.1 with the data centered at -0.96 and there is no event that appears to be a large flare. If this figure is enlarged as in Figure 10, it can be seen that in the area in which Pillitteri et al. initially observed flares, from 0.42 to 0.58 of the planets orbital period, there is no significant change of magnetic activity. This region

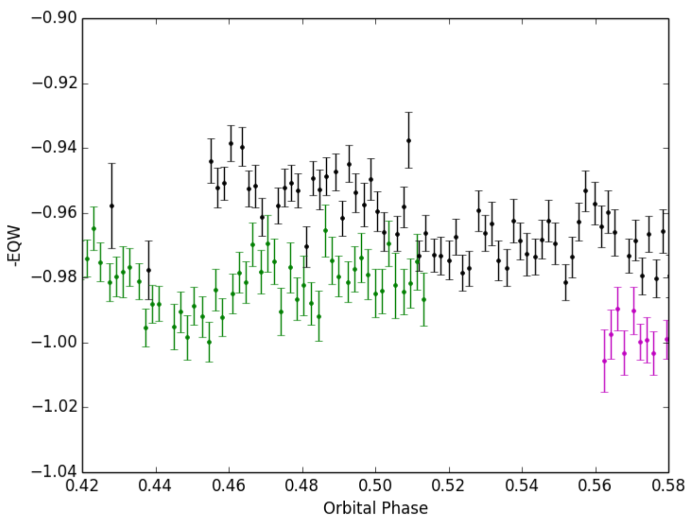

Fig. 10.— The final data zoomed in to the region shown on the original plot of Pilleterri et al. This plot shows no large spikes in the data indicating strong stellar flares.

is very nearly flat. This indicates that, at least for the periods that occurred during these observations, there were no flares. This suggests that there were not flares on HD 189733 A in the orbits of this Hot Jupiter during our observations. The scatter of this data, seen in Figures 7 and 10, of approximately 0.01 is very low, much lower than the scatter from Figure 8, which was approximately 0.25. In a star with large flares, it would be expected to see a larger variability than is seen in this data. This suggests that large flares are an extraordinary event in this star.

These conclusions are limited by the small amount of relevant data that was used here. Only one H-alpha curve covers the area of the planet's orbit in which flares were predicted to occur. The specific portion of the orbital period of HD 189733 b where Pillitteri et al. detected flares had only the observations from one night covering it. It would be ideal to have many more observations to examine if there is some other kind of larger timescale relationship between the orbital period of the planet at stellar flares on the star. The question remains as to what caused the flares that Pillitteri et al. observed originally.

In the future, it would be logistically helpful to observe only during times known to match up with the portion of the orbital period where flares are expected. It would be interesting to take more X-ray data and see if the flares show up again for some reason, but it will likely be easiest to make many more spectrographic observations and use the H-alpha method to see if there are any flares present on HD 189733 A.

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