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Differentiating the signal from the noise: towards optimal choices of transient follow-up

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ABSTRACT

With the advent of the follow-up of large localization regions from gravitational-wave detectors and gamma-ray burst transients with wide field-of-view telescopes, efficient follow-up of the many identified candidates is required. Due to limited telescope time, it is important to create prioritized lists based on the many candidates identified. Towards this end, we use models derived from GW170817 to differentiate between kilonovae, gamma-ray burst afterglows, and supernova transients. We show how to use these models to limit the lists of transients required to follow-up. We explore the dependence of the transients excluded based on the number of days of photometry and spectra available and the passbands monitored. We also investigate the effect of this reduced follow-up on estimations of the properties of the transients. We show that at least four nights of photometry are required to benefit significantly from this approach. We implement a whitening technique for the spectra model in order to increase the quality of the fit and decrease the number of days needed to identify the transients.

LAY ABSTRACT

After the recent discovery of GW170817, the first binary neutron star merger witnessed by LIGO (Laser Interferometer Gravitational-Wave Observatory), interest has developed in observing the mergers optical light, known as kilonovae, as well as their gravitational-wave signal. However, LIGO is not able to determine exactly where its signals originate on the night sky. Large swaths of the sky must therefore be examined in order to find these events. Unfortunately, since there are many other transient objects in the night sky, we need a method to quickly identify which objects could be kilonovae. My project uses models of both photometry (intensity of the light over time) and spectra and fits these models to the real signals that we have from GW170817 and other transient objects. We limit the number of days of data used to determine how many are needed to distinguish the kilonova from the other objects. We found that using four nights of data was optimal. We also implement a technique for the spectra model in which we divide out the average over all the days in each wavelength bin. This method should increase the quality of the fit and decrease the number of days needed to identify the transients.

BACKGROUND

Since the detection by LIGO of GW170817 (Abbott et al. 2017a), i.e. the binary neutron star merger, as well as its electromagnetic counterpart AT2017gfo (Kilpatrick, C. D. et al. 2017; Soares-Santos et al. 2017; Valenti et al. 2017; Arcavi et al. 2017; Tanvir et al. 2017; Lipunov et al. 2017; Abbott et al. 2017b), many theoretical models have been developed that suggest that these energetic binary neutron star mergers are the origin of the most of the elements heavier than iron, through a process called rapid neutron capture or r-process. The mergers eject these heavy, radioactive isotopes causing a powerful electromagnetic signal known as a kilonova. Although these kilonovae had been discovered previously, AT2017gfo officially connected these events to binary neutron star mergers. New models have been created to derive and constrain many of the properties of these kilonovae, but current processes are slow. A new method of quickly analyzing their photometry and spectra to identify what type of transient they are and to determine their properties is needed as the number of mergers that will be detected will only grow as LIGO increases its sensitivity.

PHOTOMETRY

GW170817 PROPERTIES

PROCEDURES

We ran the Metzger 2017 model (Metzger 2017) for kilonovae on the AT2017gfo light curves. First, we fixed the beginning of the model at the very start of the measured data. We ran the model multiple times, including ranges of data from two weeks to only one day, to determine how accurate the fits and properties would be with limited data. Since we will not always be able to detect the kilonova as early as we were able to this time, we next fixed the end point of our data at two weeks and ran the model multiple times with various starting dates from the time of the merger to a week afterwards.

RESULTS

Using the Metzger 2017 model, we fit the lightcurve data. Figures 1 and 2 show how the model degrades with fewer days of data.

Shown in Figure 3 are plots of three different properties of the kilonova: M_{ej} (ejecta mass), V_{ej} (ejecta velocity), and κ_r (opacity) as produced by the Metzger 2017 model (Metzger 2017). We can see that as we include more days of data, the values for the properties tend to converge. In the case of M_{ej}, the currently accepted value of $log_{10}(Mej)$ for GW170817 is -1.3 (Smartt et al. 2017). Clearly, we see the median converging onto this value as we increase the number of days of measurement. However, we do note that the 14 day value is too small (at only -1.18) although -1.3 is with it's error bars. This is predominantly because the Metzger 2017 model assumes the system is a blackbody, which is not as accurate of an assumption after about a week into the kilonova. Since the values for the other two properties are highly disputed, we are unable to compare them to accepted values (citations). However, we can still examine their distributions. For V_{ej}, we immediately see that the distribution begins to narrow far more between 4 and 7 days of data. We also note that the distributions for $log_{10}(\kappa_r)$ do not vary much with the amount of data, and the overall value also does not vary too much, especially given the large error bars. We also found the log likelihood for each of these fits, as plotted in the lower right corner of Figure 3. Interestingly, the likelihood tends to decrease over time, as more and more data must be fit. Presumably, this occurs because again the model is getting worse. We note that it never decreases below -11.

Knowing that the GW170817 counterpart was detected earlier than can normally be expected because of the clear location in the sky (citation), we also used a fixed end of the data at 14 days and variable beginning date. As shown in Figure 4, we see that many of the same conclusions hold for these fits as before. We do however, see a slightly wider distribution for M_{ej} that overall varies less than for the other one. This tells us that the earliest days are more necessary for determining M_{ej}. However, for V_{ej}, the distribution narrows as we use less of the early data. This could either be an effect of less data overall (though we do not see this when we fix the beginning day), or it could signify that the velocity is more accurately determined by later data. We also note that the log likelihood remains constant at about -11 (within error bars), signifying that the later data is causing far more error in the fit.

Just from looking at this data, we can make some preliminary hypotheses of thresholds from which we can determine at which point we can accurately find the properties of the kilonova. We will need to optimize between the need for later data to determine V_{ej} and earlier data to determine M_{ej}. From this, we let the preliminary threshold be 4 days of data, as long as the event is observed before a week after the merger.

DIFFERENTIATING TRANSIENTS

PROCEDURE

To test how well this model could differentiate between a kilonova and other transients, we also ran the model on three other objects: two GRB afterglows and a supernova. We again varied the number of days of data used while still fixing the beginning date. Since none of these data collections began directly at the start of the event, we did not fix the end point and vary the starting date.

However, for each of the models of these objects, we were fixing the zero point of the data. If we assume that these objects are kilonovae with a much higher thermalization efficiency than expected, the zero point would be much lower, possibly giving us more reasonable results for these other objects. Thus, we reran the model on each of the transients without fixing the zero points.

For ATLAS18qqn, we also examined the possibility that it could be much closer than originally expected - only 10 Mpc vs the originally assumed 60 Mpc. We again reran the model to see if this different distance would cause the model to produce reasonable values for this source.

RESULTS

We next fit both a supernova lightcurve (ATLAS18qqn) and an afterglow lightcurve (GRB090426) to see if the model would be able to distinguish between these two and the actual kilonova. Shown in Figures 5-6 are the (beginning fixed) fits and their theoretical properties according to the model. Neither of these data collections begin at the very start of the event, so we merely used the data that we have and took varying amounts. In looking at the properties fit by the model of these objects, we see that it would be difficult to pick out the kilonova from the others solely on this basis. The median of $log_{10}(\kappa_r)$ for each over the various numbers of days are rather small, but not implausibly so. For the GRB, both the V_{ej} and $log_{10}(M_{ej})$ are within reasonable bounds for a kilonova. The supernova is a bit more distinguishable. Both the $log_{10}(M_{ej})$ and V_{ej} over the entire range of data collection lengths are very small, erratic, and most also have two bumps, instead of a smooth distribution. These differences would be difficult to quantify, however, so a different method is necessary. Thus, the most important part of these plots to notice is the log likelihoods. While they do vary with respect to the length of time used, the GRB's log likelihood is always below -40 and the supernova's log likelihood is at or below -20. This is clearly far worse than our minimum log likelihood of -11 for the kilonova. However, it is difficult to come to a sure conclusion that we can use this to distinguish them since we only have one kilonova data point and do not know the spread of the log likelihoods.

To give more assurance that this method of distinguishing them is valid, we specifically chose a different afterglow, GRB051221A, that looks very similar to a kilonova. As we can see in Figure 7, both the V_{ej} and $log_{10}(M_{ej})$ of this GRB are within perfectly reasonable bounds, and in fact, similar to that of GW170817. However, if we look at the log likelihood for these fits, we see that the GRB's log likelihood never gets above -23, again, much lower than that of GW170817.

From this, we set a threshold for the log likelihood to identify whether a transient is a kilonova. Since we already have chosen 4 days as the minimum data necessary to accurately determine, we could have chosen a threshold as high as -7 and still selected out GW170817. However, since we only currently have one sample of a kilonova, and all of our fits of other transients never increased above -20, we chose to select a preliminary threshold of -10 allowing a large space on both sides.

However, for each of these fits, we were fixing the zeropoint of the data. If we assume that these objects could have a much higher efficiency than expected or be much closer to us than originally, the zero point would be much lower, possibly giving us more reasonable results for these other objects. Thus, we reran the model without fixing the zero points. As shown in Figure 8, the fit for GW170817 did not change much. We do see that the uncertainty of each of the properties grows, but interestingly, the median values themselves stay more constant. Unfortunately, we also note that the log likelihood using this method decreases down to -12 when we use all 14 days of data. However, our threshold of -10 still holds at 4 days of data, though with a smaller margin of error this time.

Next, we examine the three other transient objects, GRB090426, GRB051221A, and ATLAS18qqn, in accordance with this new method as shown in Figures 9-11. For GRB090426, we see that although $log_{10}(\kappa_r)$ remained consistent with a kilonova, both the $log_{10}(M_{ej})$ and V_{ej} shrunk to unlikely sizes, thus causing the fit to seem unphysical. Although this change has also reduced the log likelihood to only half as large, it is still far below our threshold of -10 and is only close once we include all 14 days of data. The properties for GRB051221A did not change much, though the distributions did spread out some. However, the log likelihoods decreased dramatically. In fact, the log likelihood at 4 days is -9, just above the threshold, so this could be a kilonova, according to our threshold. Since this object was specifically chosen because it was similar to a kilonova, this conclusion makes sense. This means that although we will be able to distinguish most other transients, some may still be incorrectly labeled as kilonovae using this method and will need visual identification or more days of observation. Finally, using this method, ATLAS18qqn also appears much more similar to a kilonova. Each of the properties are within a reasonable range. However, at 4 days, the log likelihood is -16, which is far below our threshold, which means that this method can distinguish out this object accurately.

We made one final test to determine if this method could distinguish objects where the distance had been miscalculated, thus putting the absolute magnitude at a reasonable level for a kilonova. We tested this by rerunning the model on ATLAS18qqn, this time at 10 Mpc instead of 60 Mpc. We can see the difference in the absolute magnitudes of the lightcurves in the Figures 13 and 14. As shown in Figure 12, this change caused both the $log_{10}(M_{ej})$ and V_{ej} to even out. The distributions no longer have multiple bumps and are within normal ranges for these properties. It actually looks very similar to the ATLAS18qqn fits when the zeropoint and merger time was not fixed, except even slightly better. However, once again, an examination of the log likelihood reveals that even with this better fit, the object still will not pass the threshold. At 4 days, the object has a log likelihood of about -15, which is much smaller than the threshold of -10. Thus, even if an object's distance is miscalculated, non-kilonova transients should still be filtered out by this method.

SPECTRA

WHITENING

I first created a whitening algorithm to apply to the spectra. I took the spectra of a transient object taken over several days. In each wavelength bin, I averaged over the magnitudes in each individual spectrum. I then divided out that average from that particular wavelength bin in each of the spectra. We then implemented this whitening on the expected model and then fit the whitened model to the whitened data. We chose to implement this whitening technique in order to lessen the focus of the model on the overall magnitude of the spectra and allow it to fit more of the bumps and wiggles. If this occurs, we expect to get more accurate values for both V_{ej} and $log_{10}(\kappa_r)$ since those properties mostly determine those bumps. We hope to find that this method will increase the log likelihood of the fit and thereby will have found a better overall fit of the spectral data.

FUTURE WORK

We intend to implement a similar process to that which was done with the photometry. We will test out the model on varying numbers of days of spectra from both GW170817 and other transient sources that are not kilonovae. We also wish to eventually broaden this process to include models of other transient objects in order to be able to compare log likelihoods from the fits of the various models onto an object. This will replace our current method of instituting a cutoff point into the data.

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Figure 1. Shown are the lightcurves for GW170817 using various filters when ZPT0 is fixed. The first 14 days of data are included.

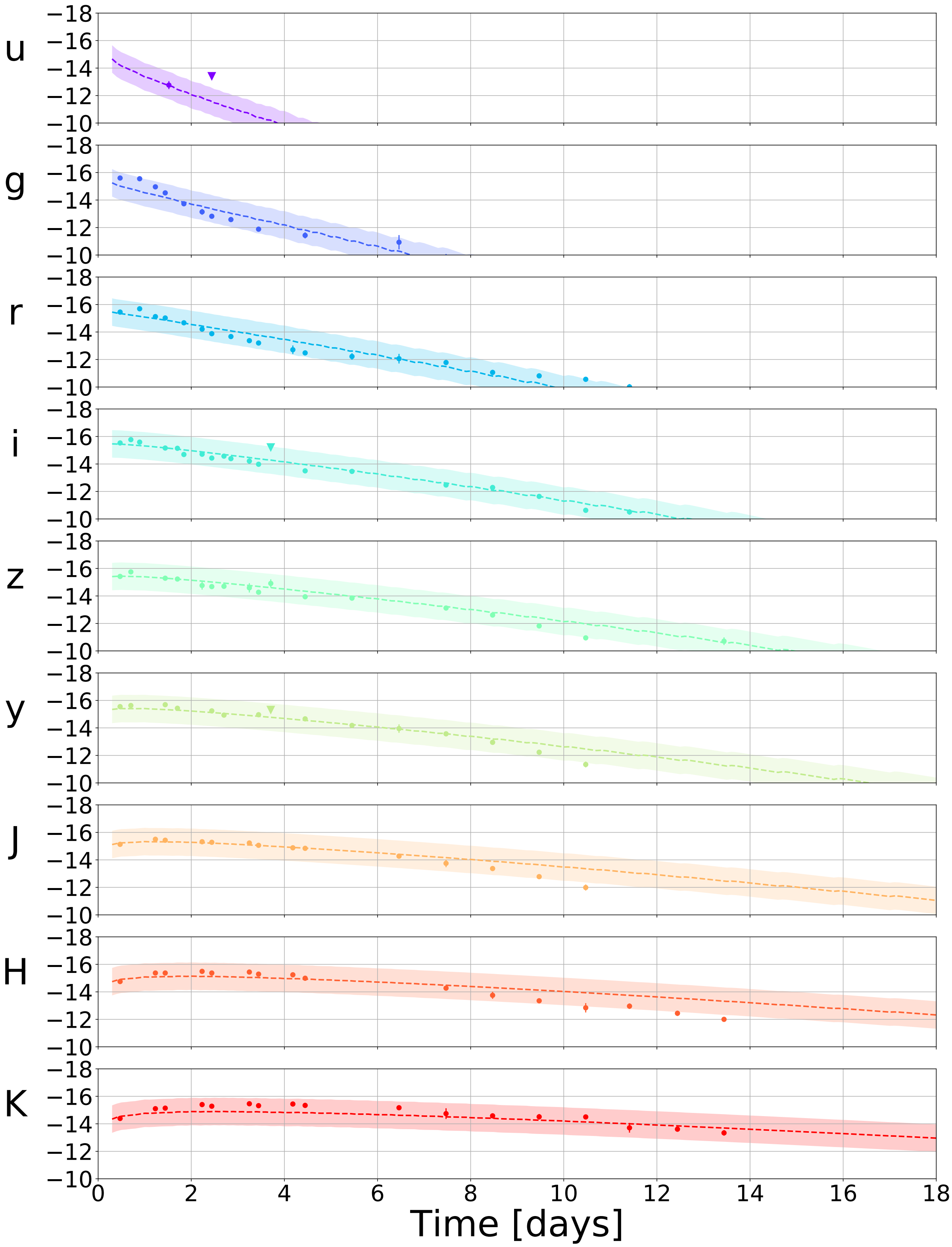

Figure 2. Shown are the lightcurves for GW170817 using various filters when ZPT0 is fixed. The first 4 days of data are included.

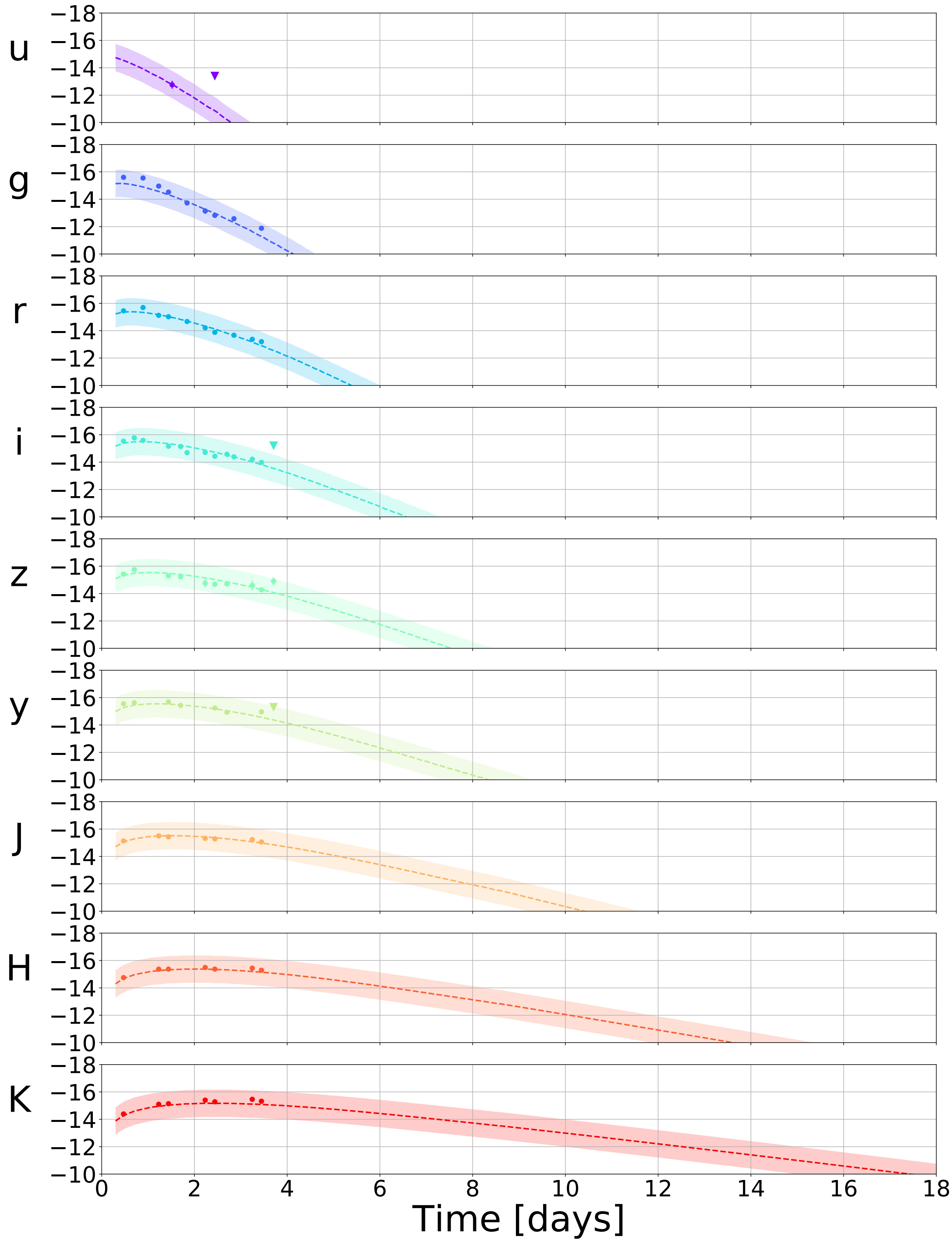

Figure 3.

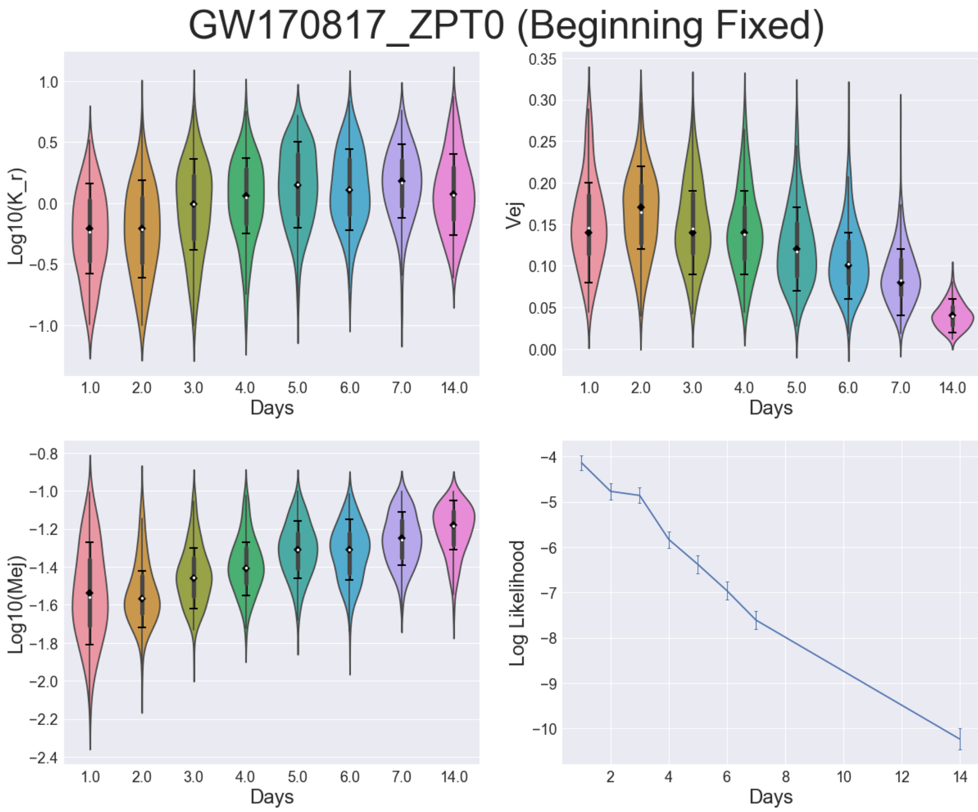

Figure 4.

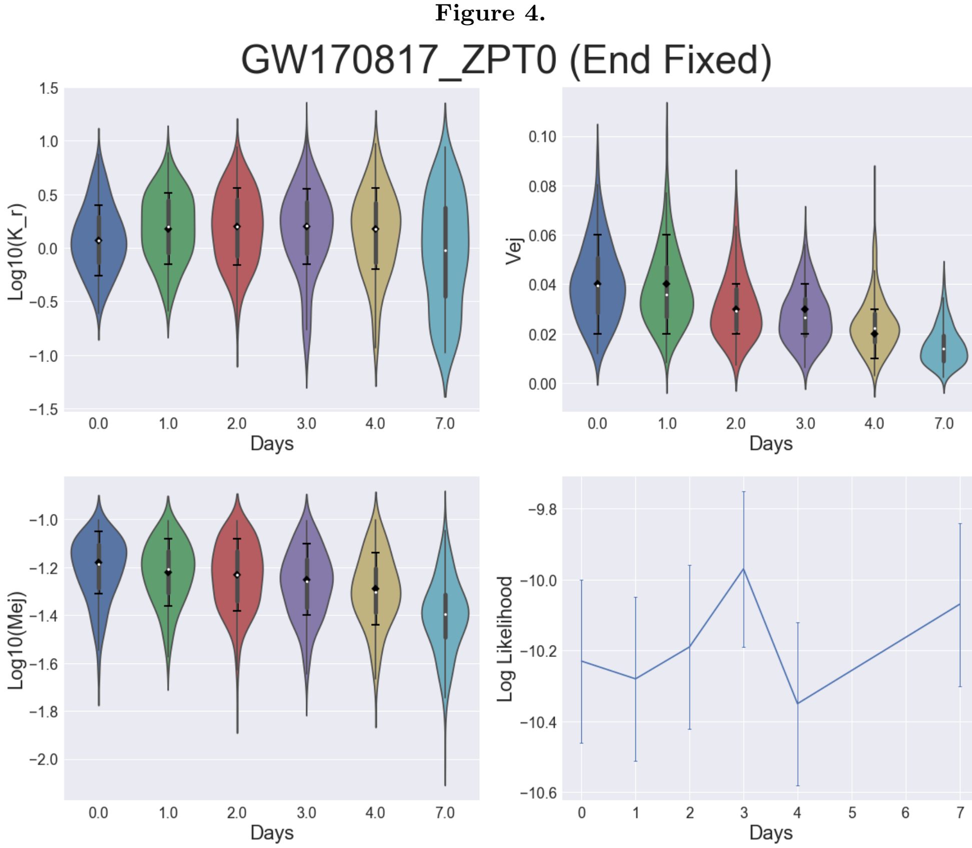

Figure 5.

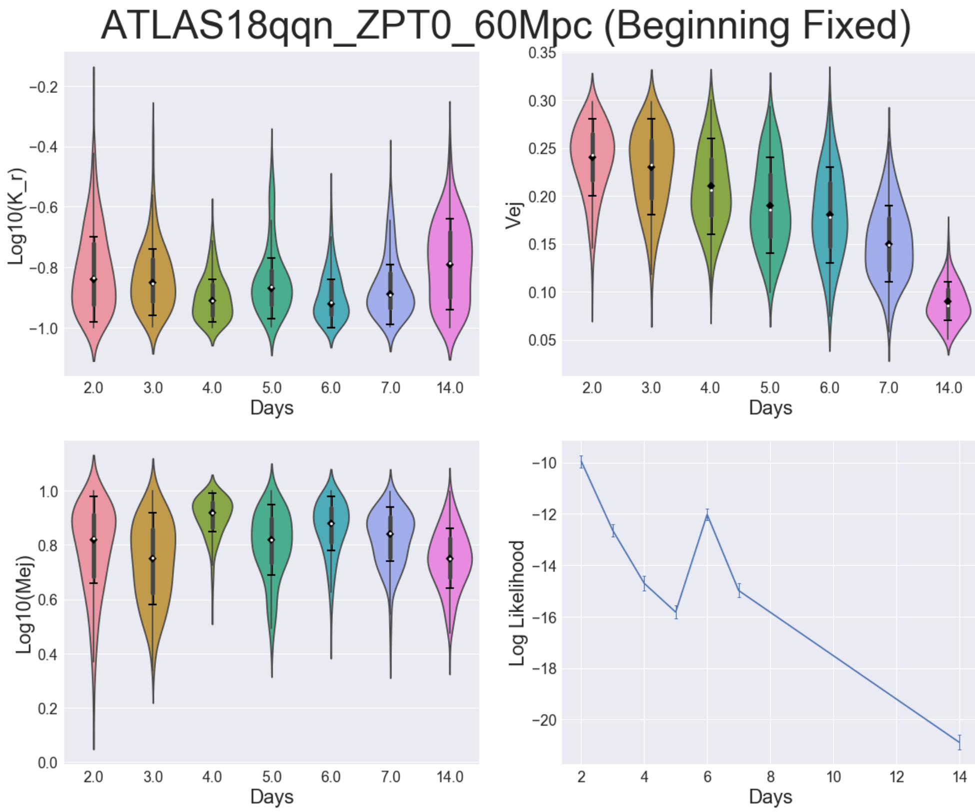

Figure 6.

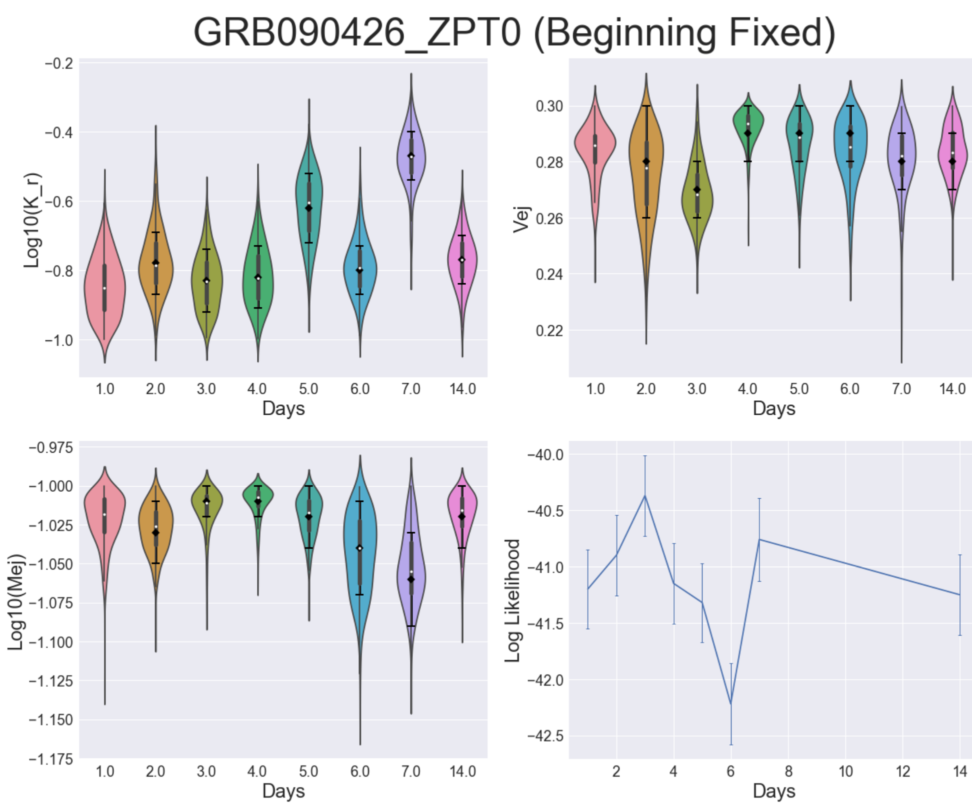

Figure 7.

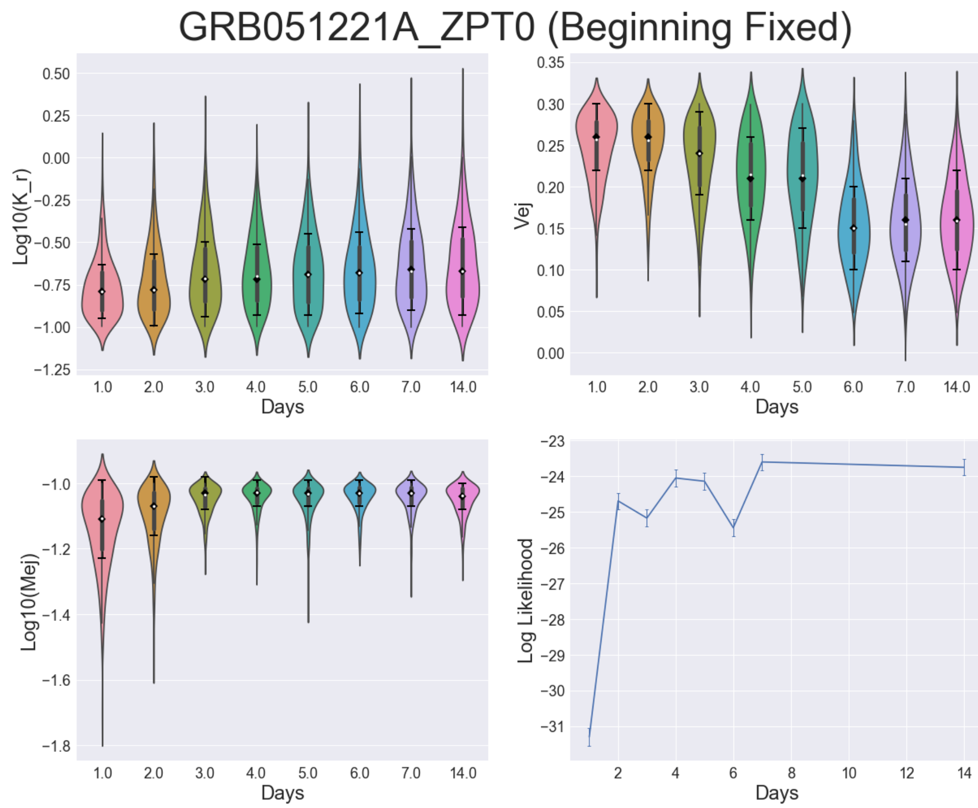

Figure 8.

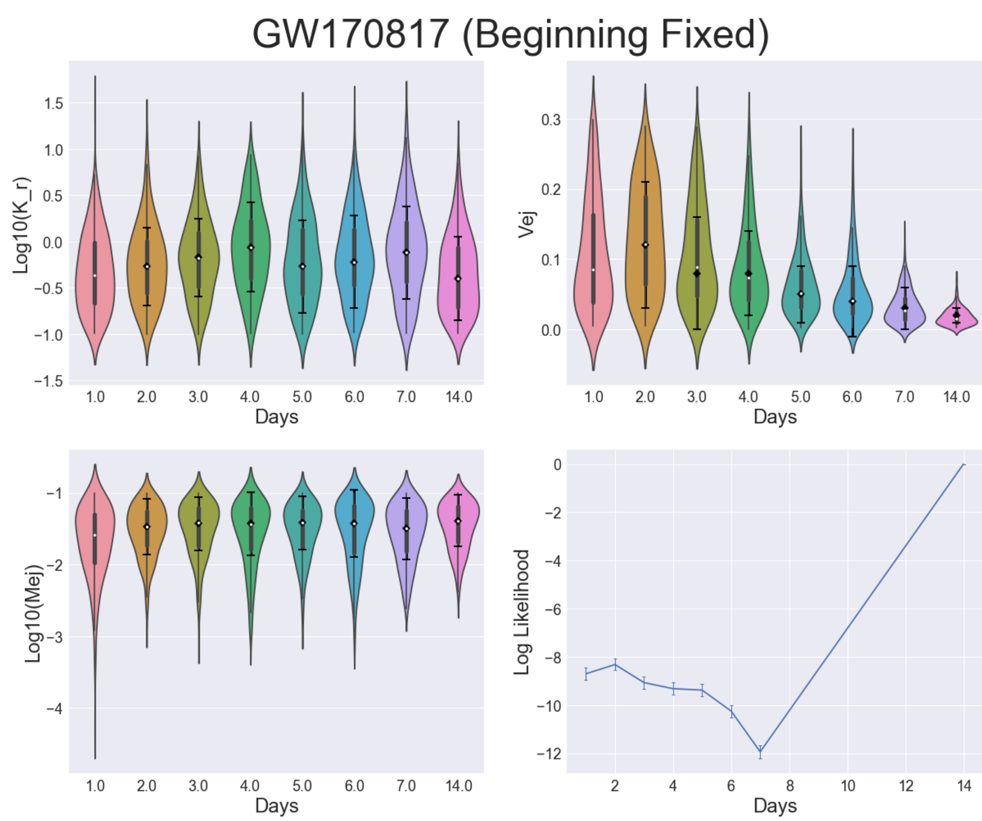

Figure 9.

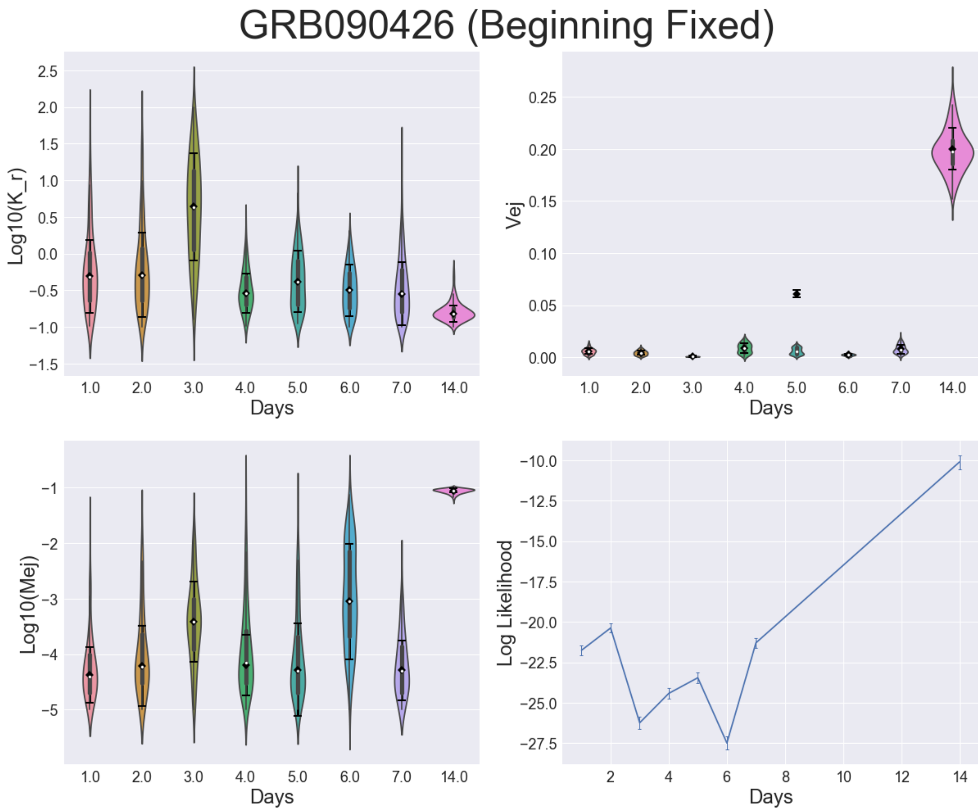

Figure 10.

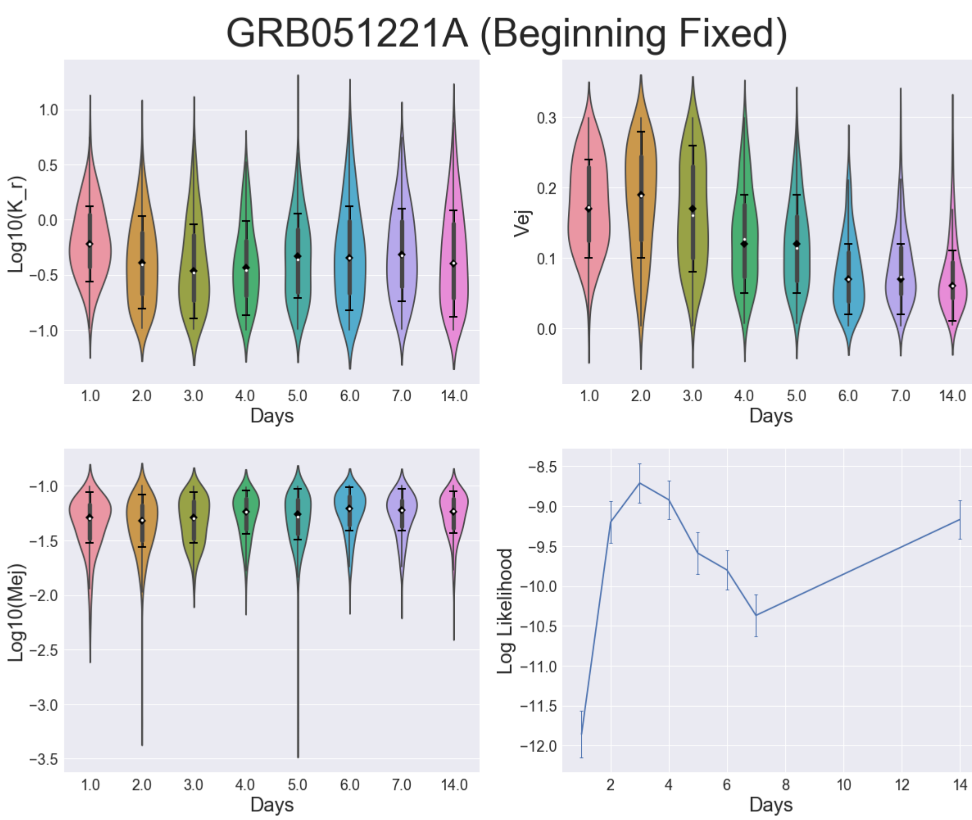

Figure 11.

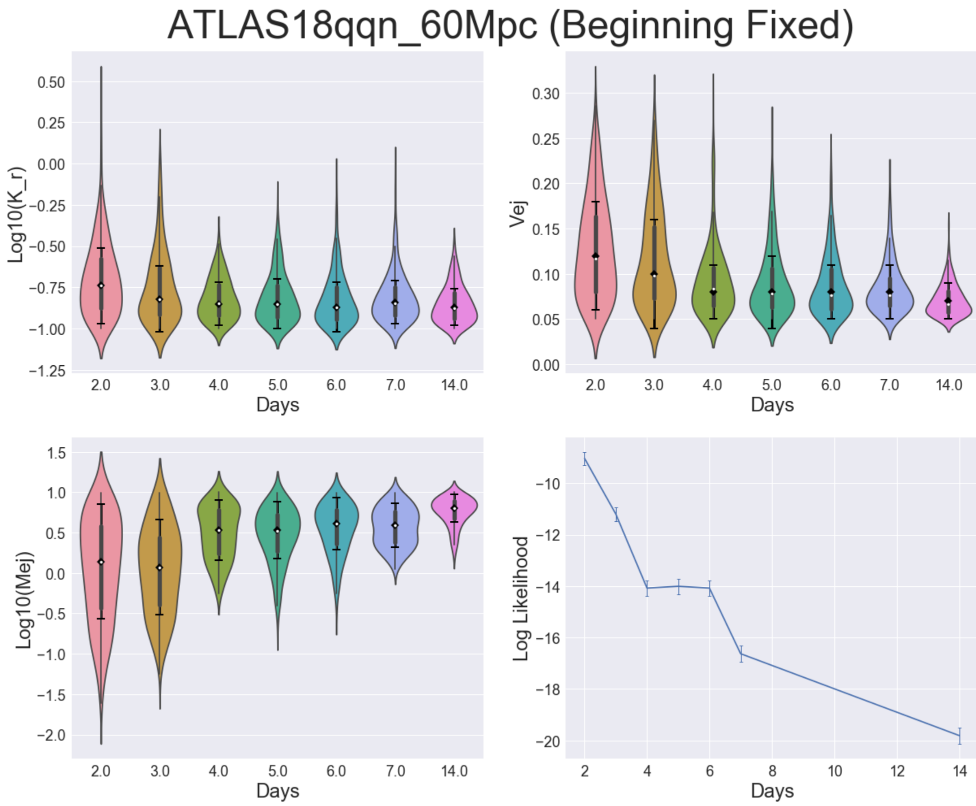

Figure 12.

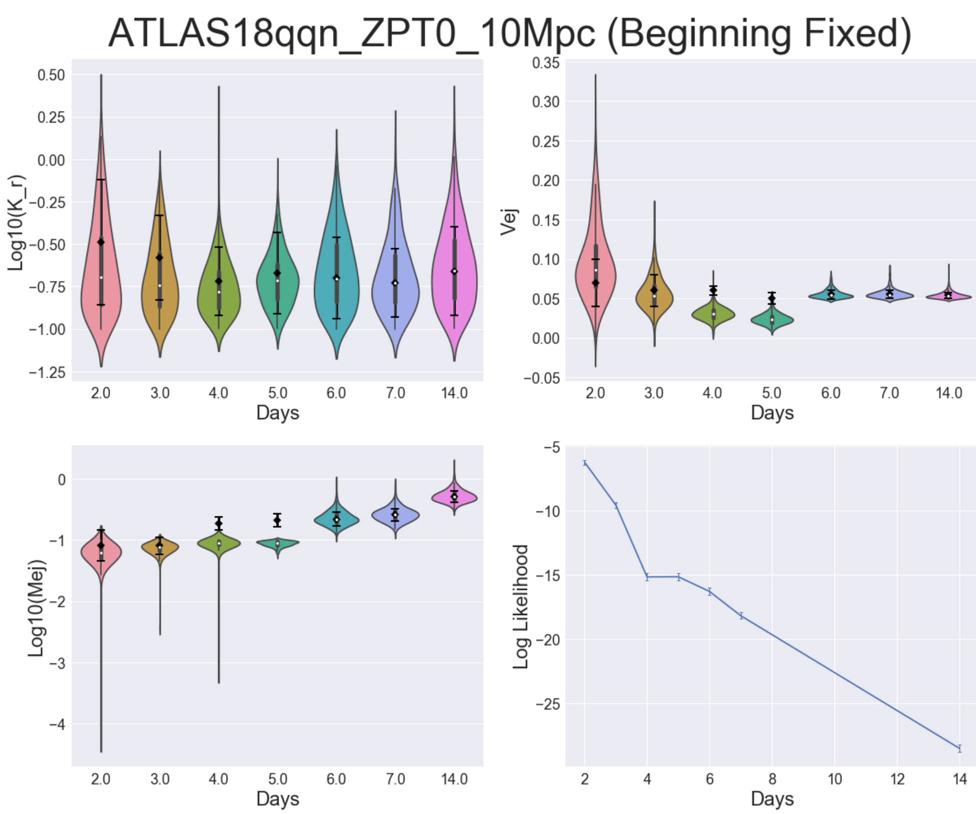

Figure 13. Shown are the lightcurves for ATLAS18qqn using various filters when ZPT0 is fixed and distance is set to 60 Mpc. 14 days of data are included.

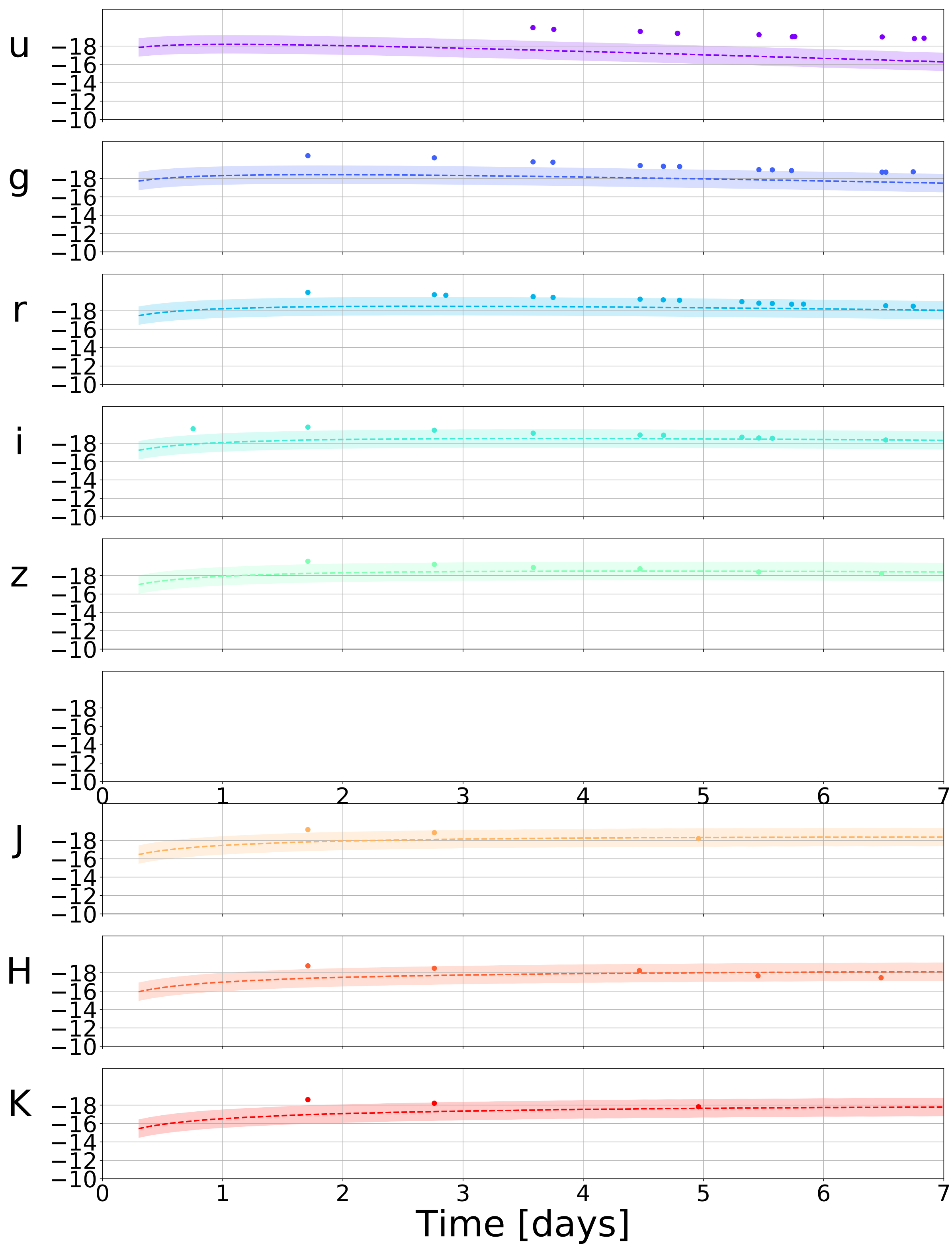

Figure 14. Shown are the lightcurves for ATLAS18qqn using various filters when ZPT0 is fixed and distance is set to 10 Mpc. 14 days of data are included.