

# The Extreme Optical Variability of J0948+0022

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## Abstract

We report on observations of the optical variability of the radio-loud, narrow-line Seyfert 1 galaxy J0948+0022 on time scales ranging from minutes to years. Implications regarding recent suggestions that the object may constitute a prototype for an emerging class of blazar-like objects similar to FSRQs are discussed. The optical microvariability observed for J0948+0022 is found to be similar to that found for a typical LBL blazar. Based on observations of J0948+0022 in a flaring state and a significantly lower state, one can demonstrate that these rapid variations are most likely originating in the relativistic jet and not in the accretion disk.

*Subject headings:* galaxies: active – galaxies: individual: J0948+0022 – galaxies: photometry – galaxies: Seyfert

## 1. Introduction

Blazars are a class of AGN that is viewed with the relativistic jet oriented near the line of sight to the observer. Observationally, they demonstrate a classic double-peaked spectral energy distribution (SED) and are detectable across the electromagnetic spectrum, notably existing in both the radio and gamma ray regimes; in some cases, these objects are even detected at energies in the TeV range. Blazars are also highly variable at all wavelengths and on all observed time scales, from minutes to years. In addition, the optical emission of blazars demonstrates significant polarization that is variable in both magnitude and position angle.

In the past few years, groups such as Abdo et al. (Abdo et al. 2009) and Yuan et al. (Yuan et al. 2008) have demonstrated that a subset of Seyfert galaxies — i.e., very radio-loud ( $R > 50$ ) narrow-line Seyfert 1s (VRL-NLSy1s) — appear to share many of the same observational traits as blazars. They have suggested that these objects constitute a new subclass of blazar. This would be of particular interest since previously blazars have exclusively been found to be hosted by elliptical galaxies, whereas Seyferts are typically found in spirals.

The prototype for this potential new class is the VRL-NLSy1 J0948+0022. It has already been shown that J0948+0022 is associated with a variable gamma ray source and that it features a double-peaked SED similar to that of a typical blazar (Foschini et al. 2011). The object is also known to be radio loud, with a radio loudness parameter  $R > \log(2.5)$  (Yuan et al. 2008). The redshift ( $z=0.584$ ) obtained by the Sloan Digital Sky Survey (SDSS) confirms that it is an extragalactic source (Adelman et al. 2008). However, although violent optical variability remains one of the hallmark characteristics of blazar activity, the optical emission of the object has yet to be thoroughly studied. This is likely due to the unfortunate faintness of the object. The authors have observed J0948+0022 to

fade to a minimum of  $m_R = 20$  during a recent, particularly faint state.

In this paper, we report on a recent monitoring program initiated to study the optical flux of J0948+0022 in an attempt to further investigate the nature of its variability and determine if it exhibits behavior on blazar-like time scales. It should also be noted that a forthcoming companion paper (Eggen et al. 2012) will detail the optical polarized emission and gamma ray emission from the object over a similar time period.

## 2. Observations

Data for this study were primarily obtained using the 72-inch Perkins, 42-inch Hall, and the 31-inch NURO telescopes at Lowell observatory in Flagstaff, Arizona. Additional observations were acquired from the 1.3 meter telescope at the Cerro Tololo Interamerican Observatory in Chile through the SMARTS consortium. Specifications for these instruments can be found in Table 1. Data from the Lowell telescopes were used to monitor intra-night to nightly trends, whereas the SMARTS telescope was used to monitor longer term behavior. Images were obtained exclusively in the standard Johnson R band. All images taken at Lowell observatory were reduced in the standard fashion. Every evening in which observations were acquired, multiple bias frames were obtained and combined into a master calibration file. Flat fielding images were taken at least once per observing run using an in-dome screen. These were then combined into a single master flat. The calibration files were then applied to all science images acquired during the observing session. Since the detectors are cooled significantly below ambient temperature, no dark frames were required. Images obtained from SMARTS were processed in a similar manner, except that the actual flat fielding and bias subtraction was done on-site by the observer in Chile to be forwarded pre-reduced to the authors.

In order to generate accurate light curves for the object and to directly compare data from different telescopes, several in-field comparison stars were selected for use in differential photometry. The object was then observed on a photometric night along with several fields containing stars of known magnitude taken from the Landolt list of equatorial stars (Landolt 1992). Images of J0948+0022 and the Landolt stars were then observed at as close to the same air mass as possible to correct for atmospheric effects. Using the known values of the Landolt objects, the true apparent (non-instrumental) magnitudes of the selected stars in the field of J0948+0022 could then be derived. The stars thus chosen are indicated in the finding chart in Figure 1.

The in-field standards were confirmed to be stellar sources using the on-line tools of the eighth data release of the SDSS. However, it should be noted that the stars were selected based entirely on the fact that they were relatively close in brightness to J0948+0022. In order to ensure that these stars are truly non-varying sources, each star was treated as an unknown object and its magnitude was derived using the other eight comparison stars in a process identical to that used to find the magnitude of J0948+0022. This was done for every image of the field taken by the three Lowell telescopes across the observing session; the SMARTS telescope was excluded from this analysis because it has a much smaller field of view and it was impossible to observe all nine stars on the same image. The resulting light curves confirm that the selected standard stars are stable. The individual R magnitudes and uncertainties of these stars are detailed in Table 2.

After the finding chart depicted in Figure 1 had been constructed, the authors became aware of another chart for the same field constructed by the Landessternwarte Königstuhl (LSW) at the University of Heidelberg, Germany. By chance, all of the stars chosen to serve as comparison objects on the LSW chart also appear in Figure 1. However, the two finding charts disagree as to the magnitudes of these stars, an issue that casts doubt onto

any published results using either source. An attempt to reconcile the differences between them is detailed in the appendix of this paper.

### 3. Results

The long-term optical behavior of J0948+0022 over the past two years is shown in Figure 2. Uncertainties for the observations shown in this figure are typically between 0.01 to 0.05 magnitudes. For purposes of comparison, the sixth standard star has been plotted on the 2012 light curve as well; the horizontal lines bounding these data indicate the range in magnitude that would be expected of the star given the observational uncertainty. In all locations where the star strays from these boundaries, it was found that the other stars also showed atypical behavior, indicating that these events are likely due to atmospheric effects rather than intrinsic variability. The check star demonstrates comparable behavior in the 2011 light curve, but this is not shown due to the fact that the check star data would have overlapped with the object data on the plot.

J0948+0022 shows extensive variability with a total observed range of 2.34 magnitudes, with a maximum brightness of  $m_R = 17.69$  occurring in May of 2011 and a minimum of  $m_R = 20.03$  in April of 2012. Remarkably, only a month after this minimum, the object had flared to nearly its previously observed peak intensity, reaching  $m_R = 17.87$ . On shorter time scales, the object demonstrates inarguable microvariable behavior. Figure 3 shows observations obtained over six nights at the end of March 2011, while Figure 4 details the same six nights on an individual basis. These nights represent the highest time resolution photometry reported to date for J0948+0022.

The optical variability behavior demonstrated by J0948+0022 is not only comparable to that of blazars both in amplitude (Noble et al. 1996) and in observed structure

(Miller & Noble 1996), but would be remarkable even by a blazar’s high standards. Clear trends well above the noise level of the standard stars can be seen in four of the six nights shown in Figure 4. On March 27, there is a slow fading of the object by  $\sim 0.15$  mag observed over 5 hours without any statistically significant short term variations superposed on this decline. On March 28, a major event is observed near 20110328.2 when J0928+0022 rapidly flares  $\sim 0.3$  mag in  $\sim 1$  hour. Following this event, a decline of  $\sim 0.15$  mag, with short-term flickering of  $\sim 0.1$  mag superposed, is observed over the next four hours. On March 29, J0948+0022 shows no evidence of significant variations as it resides near  $R \sim 19.0$  mag. On March 30, J0948+0022 exhibited two significant microvariability events with amplitudes of  $\sim 0.15$  mag and durations of  $\sim 2$  hours. On March 31, the observed variations are less well-defined due to larger errors, but there are clearly variations present with an amplitude of  $\sim 0.3 - 0.4$  mag during the night. On the night of April 1, truly spectacular variability is observed with a total amplitude of  $\sim 0.9$  mag during  $\sim 4$  hours. J0948+0022 brightened and exhibited two significant and separate events separated by  $\sim 2.5$  hours! At a rate of change of  $0.2 - 0.3$  mag/hour, this is one of the most rapid events observed for any blazar-like object.

The frequent, large-amplitude microvariability observed for J0948+0022 is consistent with the variability behavior reported for low energy peaked BL Lac (LBL) blazars (Miller & Noble 1996), a class that includes flat spectrum radio quasars (FSRQs). Thus, these results support the suggestion that J0948+0022 is more similar to FSRQ-type blazars than their high energy peaked counterparts, which are not observed to exhibit very short time scale variability at such high amplitudes.

#### 4. Conclusions

Although microvariability is one of their defining characteristics, not even the most active blazar demonstrates microvariability every night it is observed. In fact, on rare occasions even radio quiet AGN will undergo rapid optical variations within a single observing session. A more complete method of comparing the relative activity of VRL-NLSy1s to that found for blazars would be to compare their duty cycles. A duty cycle is defined as the ratio between the amount of time an object is observed in a microvarying state to the total time it was observed. Carini et al. (Carini et al. 2003) previously investigated the occurrence of microvariability in radio-quiet Seyferts, radio-loud Seyferts (where radio loudness was defined as  $R > 10$ ), and blazars. Although this earlier study suffered from a somewhat limited sample size, it was found that the likelihood of observing rapid optical variations within these classes of objects to be 10%, 19%, and 45% respectively. A similar analysis of the data presented in this paper reveals that J0948+0022 demonstrates a duty cycle of 57%, a high level of activity far more consistent with what would be expected for a blazar than a normal radio-loud Seyfert galaxy.

Given the existence of this rapid variability, it becomes possible to explore its origin. The physical cause of the optical microvariability in blazars has been a matter of discussion since the phenomenon was first shown to exist. Broadly, two possible scenarios have been put forth as likely explanations. In the first, microvariability is generated within the accretion disk of the central black hole through magnetic flares, hot spots, localized obscuration events, or any other circumstance that that could lead to a local change in brightness. The observed variability would then be caused by the combined flux from a variety of independently varying sources superimposed upon one another, neatly explaining how the flux can change so rapidly (Mangalam & Wiita 1993). Alternatively, perturbations, shocks, or bends within the relativistic jet itself could produce rapid variability (Marscher et al.



1992).

As was shown by Miller et al. (Miller et al. 2011), it is possible to distinguish between these two scenarios by observing the object in both a faint state and a bright state. Since the jet is expected to dominate the observed flux during outbursts, the relative contribution from the accretion disk will be minimized when the object is bright and largest when the object is faint. This means that any variations originating from the disk will contribute a relatively smaller portion of the total flux in the bright phase. Therefore, if microvariations originate in the accretion disk, the amplitude of the microvariability should be greatest during faint states and minimized during bright states. If the microvariability is instead caused by events associated with the jet, whenever the jet undergoes a flaring event those variations will likewise be boosted. In this case, the fractional amplitude of the microvariability will be similar in both the high and low states.

Although J0948+0022 did not undergo a major flare event during the reported observing session, Liu et al. (Liu et al. 2010) investigated the behavior of the object in a higher state during April 2009. This group indicated their observations supported a jet origin for the microvariability on their own. However, they did not consider the possibility that the microvariability could have arisen from within the accretion disk. During the night of April 25th, the Liu group observed the object to vary between  $m_R=16.7$  to  $m_R=17.3$ , with a range of microvariation of 0.5 magnitudes. This activity is comparable to what is seen in Figure 4 of this paper, in which the object was generally found closer  $m_R=18.5$ . Given the previous discussion, this suggests that the most likely origin for the microvariability is within the jet.

In a related matter, given that clear, discrete events can be detected in the microvariability it should in principle be possible to make some determination about the size of the emitting region based on light travel time arguments. Unfortunately, such an exercise

would depend on knowing the value for the Doppler boosting factor for the object. While attempts to find this value have been made using data from the VLBA (Foschini et al. 2011) such studies suffer from high uncertainties due to the compact nature of the object. Therefore, such an analysis will have to wait until more precise measurements can be made.

In summary, there is strong evidence that the characteristics of J0948+0022 are more similar to those of known blazars than typical Seyfert galaxies. In addition to the previously published double peaked SED, variable gamma ray emission, and radio footprint, the object has been shown to be strongly variable in the optical regime on both short and long time scales. Further, J0948+0022 demonstrates microvariability much more frequently than that found for other Seyfert galaxies and at a rate that is comparable to those of blazars. Finally, the nature of the observed microvariability suggests that it does not originate in the accretion disk of the central black hole, but rather in the relativistic jet.

## 5. Appendix

As mentioned in section 2 of this paper, the LSW has also published a finding chart for the field of J0948+0022<sup>1</sup>. However, the LSW chart lists different magnitudes for the stars also appearing in Figure 1 of this paper; attempts to determine the exact methodology used to derive these values were unsuccessful. Offsets of 1.25 to 1.50 magnitudes in the R band exist between the two charts. Normally, it might be assumed that the stars in question were poorly chosen variable sources. However, as detailed in section 2 these stars are known to be stable to within the uncertainty on time scales at least as long as one year. Therefore, an attempt to reconcile the differences between the charts had to be made least the results

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<sup>1</sup>The finding chart in question can be found at:  
<http://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/0948+002.html>

of this paper be called into question.

Normally, the magnitudes of standard stars are found using all-sky photometry. In the analysis presented in this paper, however, these magnitudes were derived using differential photometry and an equation of the form

$$1 : (m_{R,object} - m_{R,Landolt})_{observed} = (m_{R,object} - m_{R,Landolt})_{apparent} + k_R(X_{object} - X_{Landolt})$$

where  $m_{R, object}$  denotes both the observed and the apparent magnitudes of a chosen object,  $m_{R, Landolt}$  denotes the observed and apparent magnitudes of a star taken from the Landolt equatorial list,  $k$  is the extinction coefficient in the R band, and  $X$  is the airmass. The extinction coefficient at Lowell observatory during the time of observations was found to equal 0.03, with a standard deviation of 0.01. In turn, the J0948+0022 and Landolt fields were observed so that  $(X_{object} - X_{Landolt})$  was always less than 0.02. This implies that the  $k_R(X_{object} - X_{Landolt})$  term in equation (1) will always be on the order of  $10^{-4}$ . As the observational uncertainties are themselves on the order of  $10^{-2}$ , this term is negligible and can therefore be ignored, allowing for a straightforward calculation of the true apparent magnitude of the object once the other quantities are known.

To further check the accuracy of this methodology, an attempt was made to re-derive the magnitudes of the standard stars appearing in two blazar fields the LSW has posted on their website. The same Landolt stars used on the J0948+0022 objects were used again, and the Hall telescope had acquired all of the relevant images. This gave a total of 14 test objects. Again, the PEGA values and the LSW values were not in agreement, though this time the offsets were much smaller, ranging from 0.20 to 0.38 magnitudes. However, the blazar images had been observed three weeks prior to the observations of the Landolt stars, whereas the J0948+0022 field objects had been observed on the same night. Also unlike the Landolt fields, the blazar images were taken on a non-photometric night, and had been chosen for this analysis purely because they were the only other available fields

observed within a month of the Landolt images that the LSW also had finding charts for. It is therefore likely that the relatively minor offsets between the two sources are due to a combination of atmospheric and instrumental effects, rather than a true disagreement on the intrinsic magnitudes of these objects.

As a further check, and as a means of avoiding the issues raised in the above analysis, an attempt to re-derive the magnitudes of the four standard stars the LSW lists for the field of Bl Lac was made<sup>2</sup>. In this instance, instead of using the Landolt stars in the calculation, the magnitudes of each of the four Bl Lac stars were derived using the other three. Since both the object and calibrating stars were in the same image, any atmospheric or instrumental effects could be avoided. Using this method, exactly the same magnitudes (to within the uncertainty) were found as are listed on the LSW finding chart. This indicates that the methodology used within this paper is not the ultimate source of the disagreement for the objects in the field of J0948+0022.

Finally, a random image of J0948+0022 was chosen and a final analysis was performed on the stars selected by each group. First, in a method similar to the above, the magnitudes of the nine stars appearing in Figure 1 were calculated by treating each as an unknown object and using the other eight as standards. The PEGA values were assumed to be correct for each star’s true apparent magnitude. All nine objects were found to have the expected magnitudes, with the highest deviation being 0.05 magnitudes for star 9 (star C on the LSW list). This value is just above the associated uncertainty for the object.

The same analysis was then performed on the three stars appearing on the LSW chart using the magnitudes they claim for each object. In this instance, much higher deviations from the expected values were observed, with star C (number 9 in the PEGA list) again

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<sup>2</sup>The Bl Lac chart can be found at: <http://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/220>

being the worst offender with a deviation of 0.18 magnitudes. Therefore, unlike those listed in this paper, it appears that the LSW values for these stars are not internally consistent.

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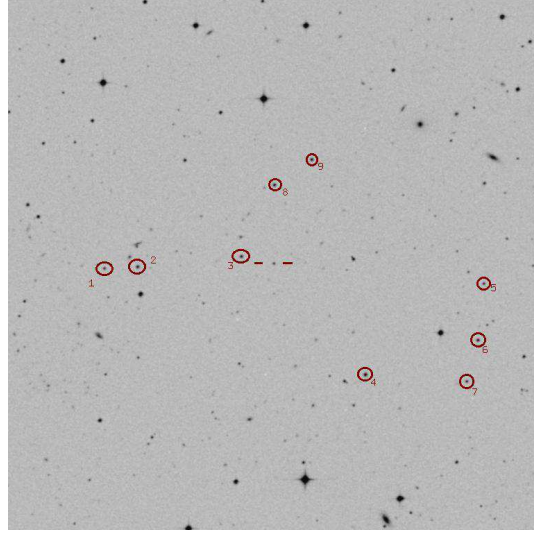


Fig. 1.— Finding chart for J0948+0022 with object highlighted. Field of view is 12.9' x 12.9'

Telescope	Observatory	Detector	Scale (arcsec/pix)	Field of View
Perkins	Lowell	PRISM	0.780 (2x2 binning)	13.3' x 13.3'
Hall	Lowell	NASA42	0.740 (2x2 binning)	25.3' x 25.3'
NURO	Lowell	NASAcam	0.456	15.6' x 15.6'
1.3 meter	CTIO	ANDICAM	0.371	6' x 6'

Table 1: Instrument Specifications

Star Number	1	2	3	4	5	6	7	8	9
Magnitude	18.64	17.62	17.84	17.11	18.53	17.77	18.46	17.74	17.74
Uncertainty	0.04	0.02	0.02	0.03	0.05	0.04	0.02	0.03	0.04

Table 2: Check star information for Figure 1.

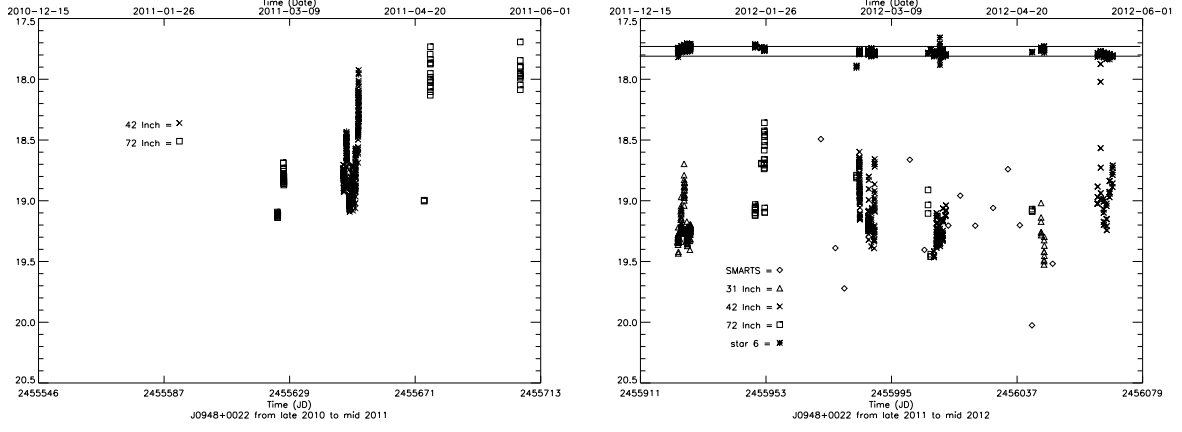


Fig. 2.— Monthly light curves for J0948+0022 for 2011 (left) and 2012 (right). All images were taken in the R band.

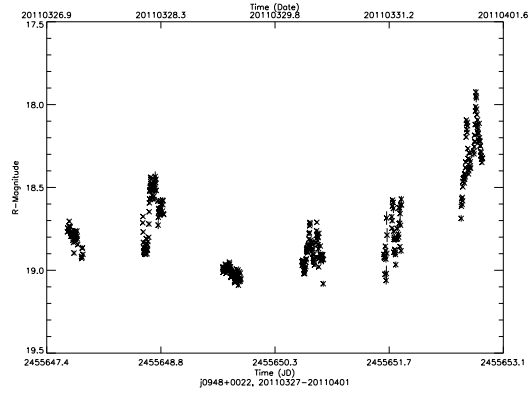


Fig. 3.— Behavior of the object on a nightly timescale. Data was obtained exclusively from the Hall telescope on the nights of March 27 - April 1, 2011.



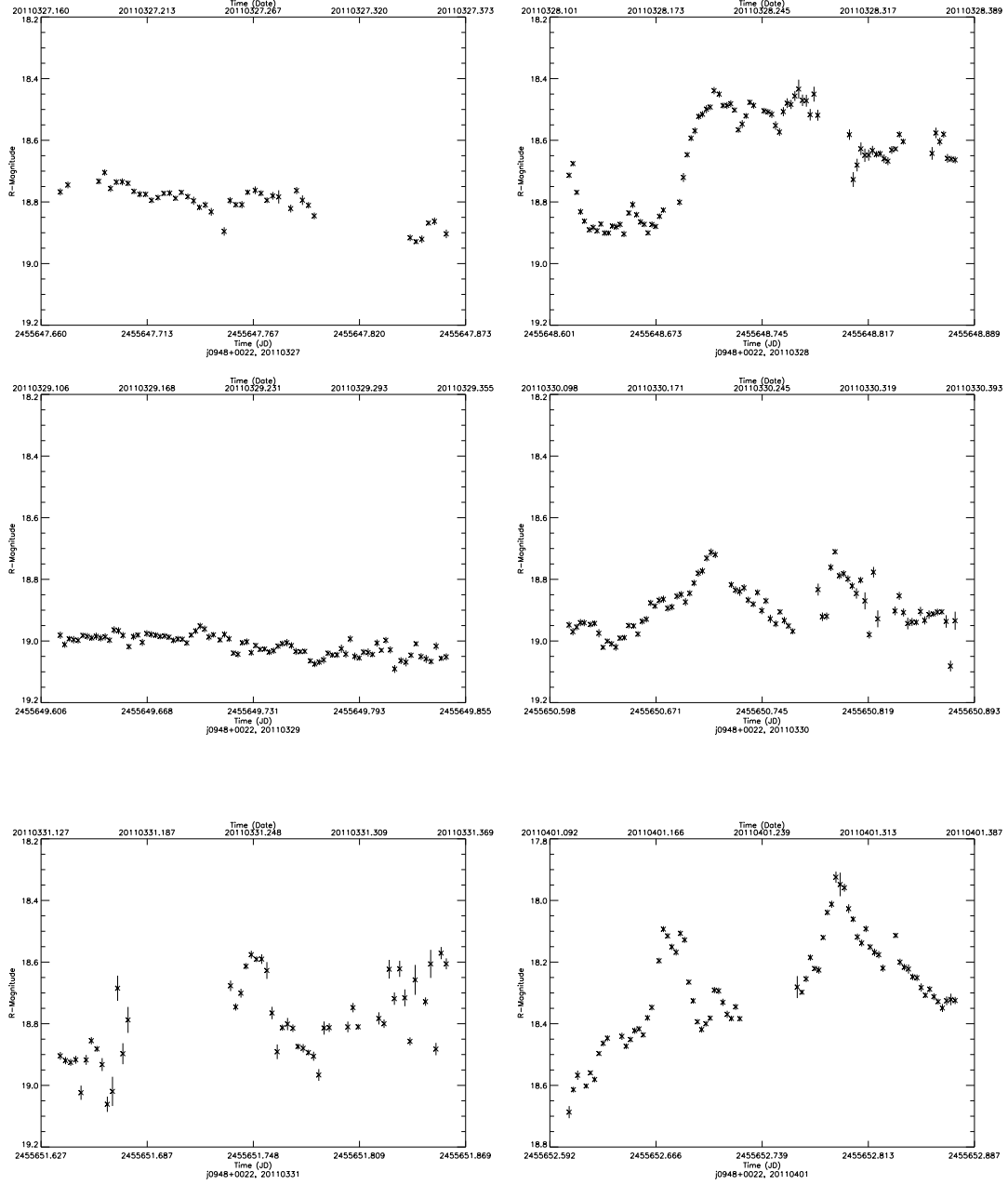


Fig. 4.— Microvariability behavior of J0948+0022 across the same six nights as the previous figure. All light curves are plotted on a one-magnitude scale, though that of the final night (April 1<sup>st</sup>) is displaced slightly from the previous five. Calendar dates are given in yyyyymmdd.xxx format, where xxx is the fractional day.