Wild Weather: Brown Dwarfs with Dynamic, Rapidly Changing Clouds

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Abstract. Brown dwarfs have exotic clouds made of silicates and molten iron. Uneven distribution of these clouds over a brown dwarf's photosphere will cause the object to exhibit periodic flux variations as it rotates. Several brown dwarfs that vary in this way have been discovered. Others, however, have been found to exhibit non-periodic variations. As recently as two years ago, the reality of these was regarded with skepticism — quite reasonably, since measurement systematics can mimic non-periodic variations, and theory did not predict the swift, global changes in brown dwarf cloud distributions that the data seemed to imply. However, new evidence shows that aperiodic variability is real: the photometric amplitude and phase of some brown dwarfs do change on a rotational timescale. We present four new brown dwarfs with confirmed aperiodic behavior, and show that there is a wide range in the degree of their departure from perfect periodicity. The extent of this departure should be determined mostly by the rapidity of cloud evolution on the brown dwarf, and therefore aperiodicity constitutes a direct probe of the atmospheric dynamics of these fascinating objects.

1. Variable Brown Dwarfs in the Weather on Other Worlds Program

Observations from the Weather on Other Worlds (WoW) program using the Spitzer Space Telescope have identified twenty-one variable brown dwarfs, most of them previously unknown (Metchev et al. 2014). Spitzer's stable, space-based vantage point is ideal for distinguishing genuine aperiodic variability from instrumental effects.

WoW monitored each brown dwarf for about 14 hr in the IRAC 3.6 μm band and 7 hr in the IRAC 4.5 μm band. We have fit the normalized photometry of each object as a truncated Fourier series, using the smallest number of Fourier terms sufficient to yield residuals consistent with random error. In many cases we can find a reasonable Fourier model that simultaneously and consistently fits the measured photometry across both IRAC bands, where the amplitude is allowed to be different between the two bands but the phase and waveform are held fixed (Metchev et al. 2014). In other cases, however, such fits require an implausibly large number of Fourier terms and have long best-fit periods comparable to the full duration of the photometric monitoring. We describe such fits as implausible because they have prominent peaks and troughs that are very narrow relative to the full fitted period. Such narrow peaks and troughs, together with the large numbers of distinct local extrema that usually accompany them, can occur in rotational lightcurves only for specific, highly improbable distributions of the photospheric brightness. In simulations where, e.g., photospheric spots are allowed to be randomly distributed in longitude, smoother, simpler lightcurves with broad peaks and troughs almost invariably result (see Section 3.).

Failure to find a plausible simultaneous fit to both the 3.6 μm and 4.5 μm photometry from a given object could in principle result from wavelength-dependent phase shifts, or other differences between the 3.6 μm and 4.5 μm lightcurves that are not captured by our Fourier model. However, four objects exist for which even the fit to the 3.6 μm data by itself is implausibly complex. We confine our current analysis to these four objects, which exhibit the strongest evidence for irregular variations in the WoW sample.

2. Four Aperiodic Variables

We list these four highly aperiodic variables in Table .1, together with the shortened designations for them that we will use hereafter. In Figure .1 we contrast the 3.6 μm WoW photometry of a periodic object, the L6 dwarf 2MASSI J0103320+193536 (hereafter 2MASS 0103) discovered by Kirkpatrick et al. (2000), with that of the aperiodic L4.5 dwarf 2MASS 1821. In Figures .2 and .3, we show our remaining three aperiodic variables.

The sequence of objects shown in our three figures — 2MASS 0103, 2MASS 1821, 2MASS 1507, SDSS 1043, and SDSS 0107 — is ordered by the increasing extent of the objects' aperiodicity, where this is defined by the difficulty of determining the true rotation period. 2MASS 0103 is cleanly periodic. For 2MASS 1821 the rotation period is clearly 4.2 hours, but variations in the mean flux and/or amplitude demand a fit with four Fourier terms and a nominal period a factor of two longer than the true one. 2MASS 1507 and SDSS 1043 exhibit sufficiently irregular variations that their periods are not visually apparent, but periodogram analyses of both the 3.6 μm and 4.5 μm data (not plotted) allow us to identify dominant frequencies for each object, which we believe correspond to the rotation periods. For the L8 dwarf SDSS 0107, the variations are so irregular that no dominant frequency can be confidently identified. Thus, the objects in this sequence represent a continuum of increasingly aperiodic behavior. The parameter that defines this continuum is likely to be the ratio of the rotation period to the cloud evolution timescale. Where this ratio is very small, implying that the clouds evolve slowly over many rotation periods, we see periodic variability like that of 2MASS 0103. Where the ratio approaches unity, the clouds evolve so fast that the rotational signal can disappear.

Table .1: Aperiodic Variables

Object Designation	Short Name	Spectral Type	Probability of Periodicity[a]
SDSSp J010752.33+004156.1[b]	SDSS 0107	L8[c]	4×10^{-3}
SDSS J104335.08+121314.1[d]	SDSS 1043	L9[e]	$\leq 5 \times 10^{-5}$
2MASSW J1507476-162738[f]	2MASS 1507	L5[f]	$\leq 5 \times 10^{-5}$
2MASS J18212815+1414010[e]	2MASS 1821	L4.5[e]	10^{-3}

[a]The probability, based on our calculation discussed in the text, that a rotationally modulated, strictly periodic lightcurve would appear as complex as the one observed for this object.

[b]Geballe et al. (2002). Footnotes on designations are discovery credits.

[c]Hawley et al. (2002)

[d]Chiu et al. (2006)

[e]Kirkpatrick et al. (2010)

[f]Reid et al. (2000)

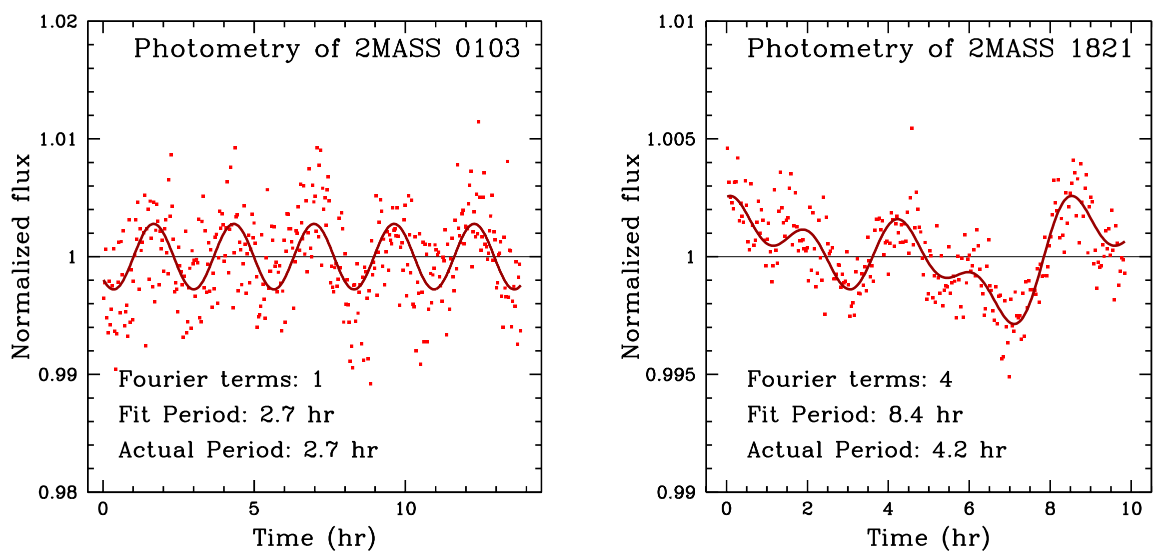

Figure .1: Normalized IRAC 3.6 μm photometry of two WoW brown dwarfs, showing the lowest-order Fourier fits to yield acceptable residuals. **Left:** The L6 dwarf 2MASS 0103 is perfectly periodic to within the limits of the data. **Right:** The L4.5 dwarf 2MASS 1821 has a clear 4.2 hr rotation period, but its amplitude and mean brightness evolve such that only a fit with double this period can yield residuals consistent with random noise.

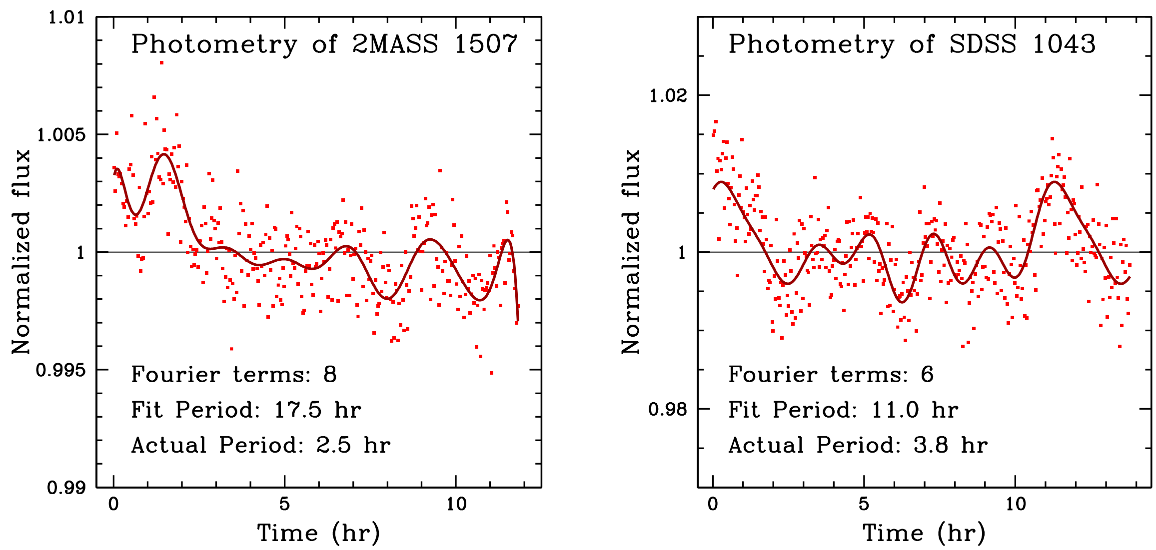

Figure .2: Normalized IRAC 3.6 μm photometry of two WoW brown dwarfs, showing the lowest-order Fourier fits to yield acceptable residuals. **Left:** The period of the L5 dwarf 2MASS 1507 is not obvious visually, but we have determined it using additional 4.5 μm photometry and periodogram analyses. **Right:** Like 2MASS 1507, the L9 dwarf SDSS 1043 shows irregular variations whose dominant frequency, determined using both 3.6 μm and 4.5 μm data, reveals the object's rotation period.

3. Are They Really Aperiodic?

We have claimed that four of the variable brown dwarfs discovered by WoW exhibit aperiodic variations, based on the complexity of the lowest-order acceptable Fourier fits to the 3.6 μm photometry of these objects. Here we address two possible objections to this claim. First, it could be objected that the apparently aperiodic variations are due to systematic effects in the Spitzer/IRAC photometry. Second, the objects might be strictly periodic variables with unusually complex lightcurves.

To address the first objection, we note that the dominant systematic effects in IRAC photometry are well understood and have been modeled and removed from our data. Some very weak non-random residuals remain. To quantify the extent to which they can affect our photometry of brown dwarfs, we have painstakingly analyzed the photometry of more than 600 WoW field stars (Metchev et al. 2014). This analysis indicates that residual systematics are far too small to produce false indications of aperiodicity at the level observed in the objects we discuss herein.

We have addressed the second concern using Monte Carlo simulations of photometry from rotating objects. We quantify the complexity of an object's lightcurve using the width of the highest peak and deepest trough, measured at a distance of one-third the total amplitude below the peak or above the trough, respectively. These measurements are illustrated in Figure .3 for SDSS 0107. The narrower the peak and trough relative to the photometric

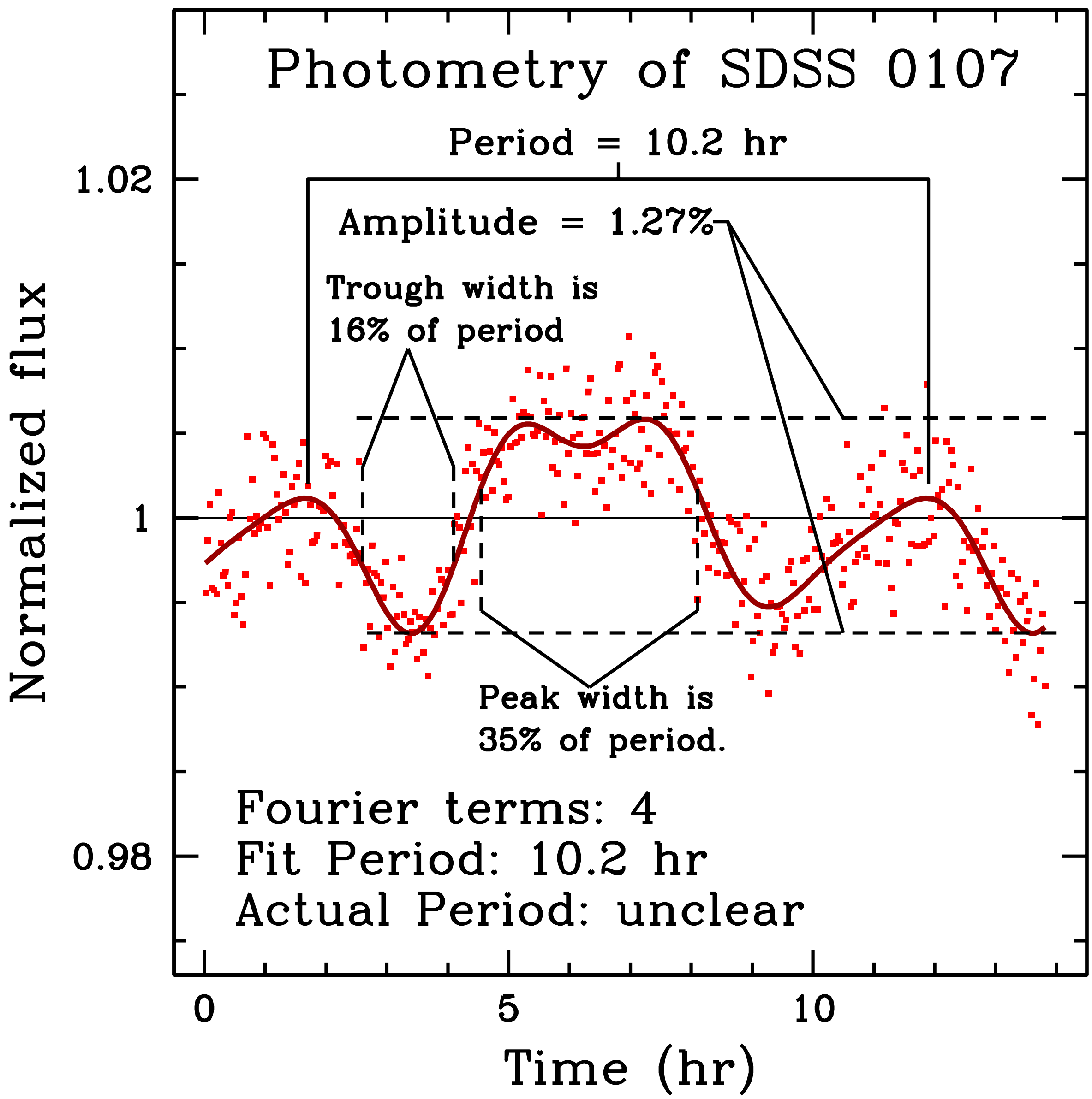

Figure .3: Normalized IRAC 3.6 μm photometry of our fourth aperiodic variable, the L8 dwarf SDSS 0107, showing the lowest-order Fourier fit that yields acceptable residuals. The variations of SDSS 0107 are so irregular that no dominant frequency can be confidently determined, and the true rotation period remains unknown. We illustrate the definitions of the peak and trough widths used in our Monte Carlo simulations (Section 3.). These measurements are made only for the highest peak and deepest trough, and the widths are defined at a vertical distance equal to one-third the full amplitude from the respective extrema.

period, the less likely the lightcurve is to arise from strictly periodic, rotationally modulated variability.

For our Monte Carlo analysis, we create simulated rotational lightcurves of objects with 60–100 small, randomly placed photospheric spots. Analogy to the giant planets in our own Solar System would suggest that brown dwarfs have instead a small number of larger cloud features (e.g., Jupiter's Great Red Spot) — however, there is no certainty that this analogy holds, and in any case narrow peaks and troughs are even more improbable where the number of spots is small. The 60–100 spots on our simulated objects are intended to approximate an arbitrary, unconstrained distribution of photospheric brightness. For each of our aperiodic brown dwarfs, we run a separate Monte Carlo analysis consisting of 2×10^4 lightcurve realizations. We calculate the fraction of these simulated lightcurves for which both the highest peak and the deepest trough are at least as narrow as the corresponding features in our best-fit Fourier model of the 3.6 μm photometry of the brown dwarf in question; and we report this fraction as the probability that the brown dwarf's variations are in fact periodic. This probability is 10^{-3} for 2MASS 1821, 5×10^{-5} or less for 2MASS 1507 and SDSS 1043, and 4×10^{-3} for SDSS 0107. All four objects are therefore genuinely aperiodic at a level of confidence high enough that no false positives would be expected among the WoW sample of 21 variables.

4. Conclusion

We have identified four L dwarfs with aperiodic variations. These can be placed on a continuum of increasingly aperiodic behavior that also extends backward to include other WoW variables whose lightcurves are more nearly periodic. Imperfectly periodic brown dwarfs identified by other studies (e.g. Radigan et al. 2012, Apai et al. 2013, Gillon et al. 2013) fit into the same continuum, though their departures from periodicity were less extreme in most cases. This continuum is probably defined by the ratio of the rotation period to the cloud evolution timescale. The latter can be short enough to make even a fast-rotating brown dwarf such as 2MASS 1507 exhibit strongly aperiodic variations. Although the WoW sample included comparable numbers of both L and T dwarfs, the four most definitive aperiodic variables all have L spectral types, which may suggest that clouds evolve more rapidly on warmer objects (Metchev et al. 2014). Even among the L dwarfs, however, there appears to be a wide range in the rapidity of cloud evolution, and the underlying physical reasons for this currently remain obscure.

While we tend inevitably to think of brown dwarfs as self-luminous versions of Jupiter with stable cloud features analogous to the Great Red Spot, the latest observational evidence suggests that a substantial minority of them experience extremely rapid, global cloud evolution with no parallel in the Solar System. The investigation of such dynamic 'weather' holds promise for fascinating future results in both theory and observation — as does the question of why the timescale for cloud evolution can be so different for different brown dwarfs.

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