LONG-TERM SPECTRAL/TIMING CHANGES IN SWIFT J1357.2–0933 REVEAL AN EVOLVING JET IN QUIESCENCE

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ABSTRACT

We present six years of optical monitoring of the black hole candidate X-ray binary Swift J1357.2–0933. On these long timescales, the quiescent light curve is dominated by high amplitude, short term variability spanning ~ 2 magnitudes, with an increasing trend of the mean flux from 2012 to 2017 which is steeper than in any other X-ray binary found to date. We detected the early rise of the 2017 outburst of Swift J1357.2–0933, and we report the outburst began between April 1 and 6, 2017. Such a steep optical flux rise preceding an outburst is expected from disc instability models, but the high amplitude variability in quiescence is not. Previous studies have shown that the quiescent spectral, polarimetric and rapid variability properties of Swift J1357.2–0933 are consistent with synchrotron emission from weak compact jets. We collect all optical–infrared data taken during quiescence since 2006 from transient surveys and the literature. We find that a changing spectrum is responsible for the brightening, with the optical/infrared emission describing a power law which evolves from a steep, red slope before and soon after the 2011 outburst, to one which is flatter since 2013. The evolving spectrum reveals long-term changes in the frequency of the jet spectral break; the break shifts from the infrared in 2012 to the optical in 2013, then back to the infrared by 2016–2017 while the optical remains relatively bright. The result is an overall increase in the u-band flux of a factor of ~ 14, an increase in the I-band flux of a factor of ~ 4–6, and almost no change at all in the infrared flux. Swift J1357.2–0933 is a valuable source to study black hole jet physics at very low accretion rates, and possibly the only quiescent source in which the jet properties can be regularly monitored.

INTRODUCTION

It has been known for more than a decade that accreting black holes can launch jets at very low accretion rates, when the X-ray luminosities are less than ~ 10^{-5} of the Eddington luminosity. At optical wavelengths, long-term monitoring studies of quiescent low-mass X-ray binaries (LMXBs) have revealed the ellipsoidal modulation of the companion star in some systems, and flickering, flares and/or variability from the accretion flow. OIR (optical-infrared) synchrotron emission has been detected in some LMXBs during quiescence. In Swift J1357.2–0933 it appears to dominate the quiescence OIR spectrum. High amplitude, seconds to hours-timescale optical variability, a red or flat spectral energy distribution (SED; Shahbaz et al. 2013; Plotkin et al. 2016) and evidence for intrinsic polarisation at a level of 8.0 ± 2.5 % (Russell et al. 2016) are all unique properties that cannot be produced by the accretion disc, advection dominated flows or the companion star. However, emission from the jet can account for all these properties. This has led to the conclusion that jets are continuously launched during quiescence.

DATA COLLECTION

We have conducted a long-term monitoring campaign of Swift J1357.2–0933 with the two, robotic 2-m Faulkes Telescopes (North, a Maui, Hawaii, USA, and South, at Siding Spring, Australia) since its outburst in 2011. Data were also taken in 2017 with some of the 1-m network Las Cumbres Observatory (LCO) telescopes. A search of the literature was also performed to gather OIR photometry measurements during quiescence (and some during outburst).

RESULTS AND ANALYSIS

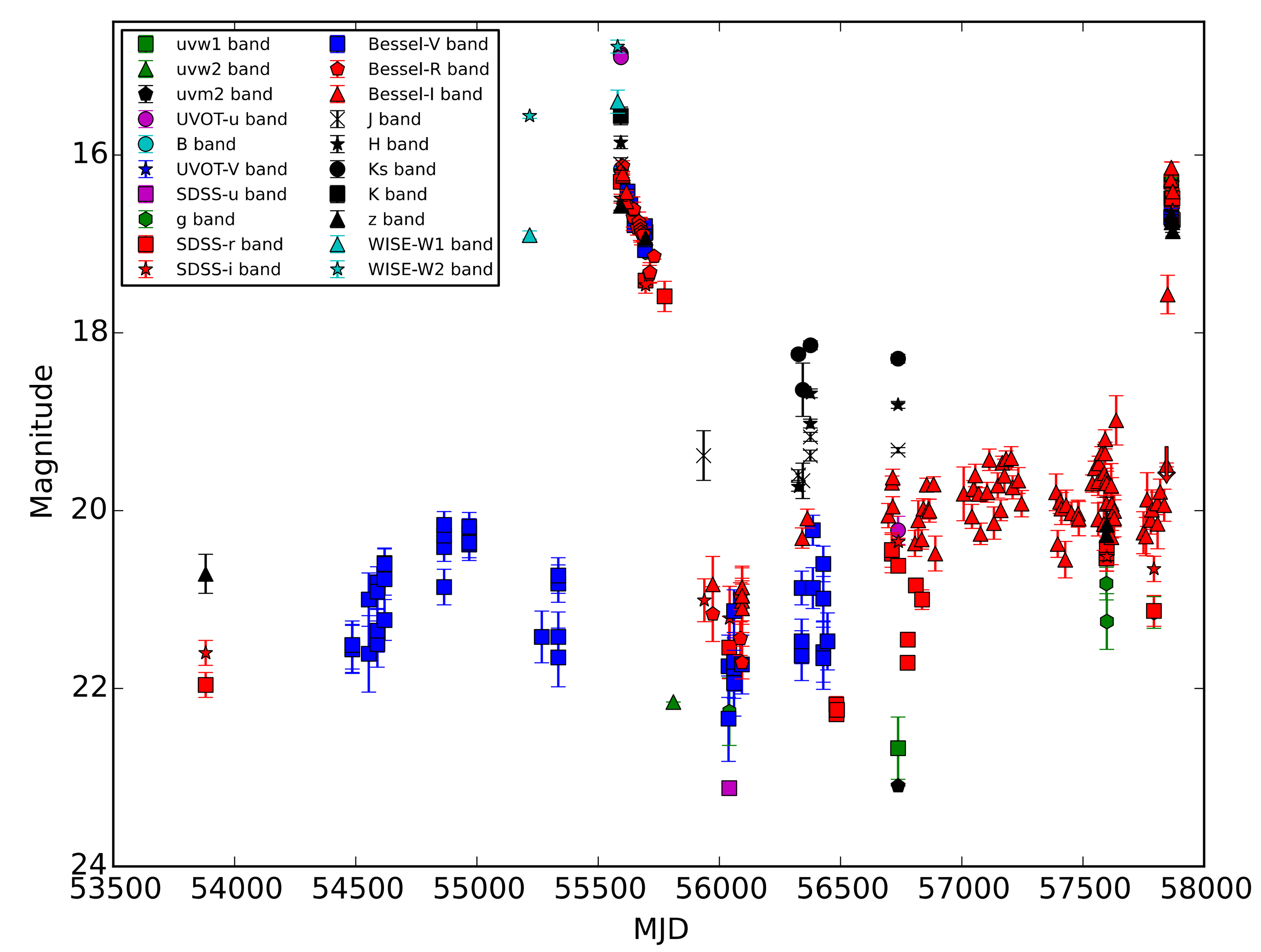


Figure 1. OIR light curves of Swift J1357.2–0933 from 2006 to 2017. The 2011 and 2017 outbursts are evident near the center and right, respectively. Large amplitude variability is present in quiescence before and between the two outbursts. The I-band magnitudes span a range from I ~ 21.1 to I ~ 19.0 during quiescence. This is much greater amplitude than expected from ellipsoidal modulation of the companion star. The majority of the emission must therefore be produced by the accretion flow or reprocessing. We still consider the source to be in a state of quiescence despite the strong variations, because the X-ray luminosity is very low.

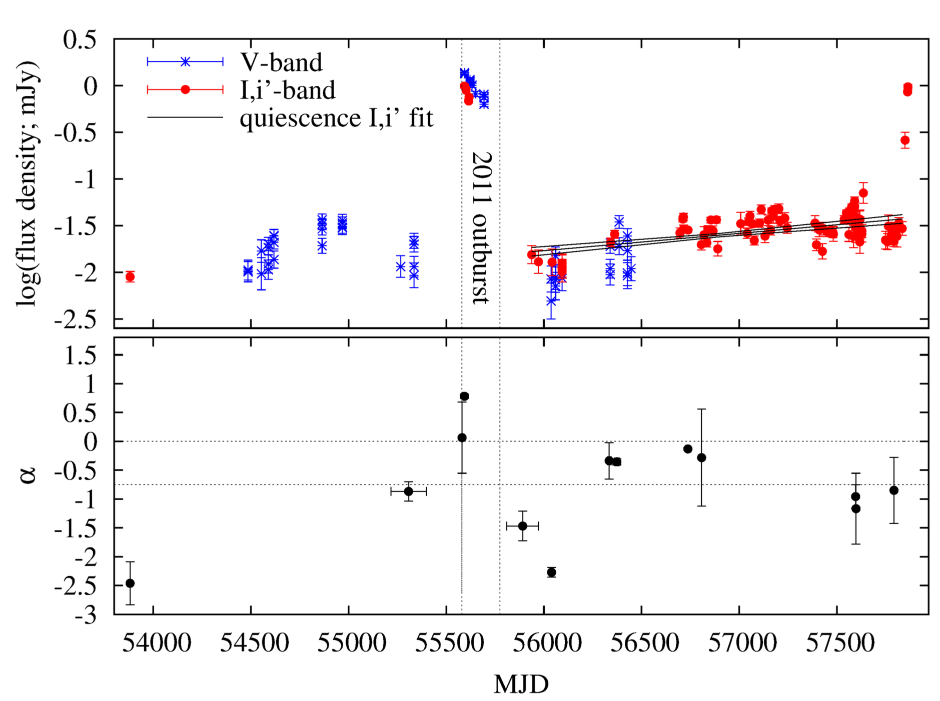
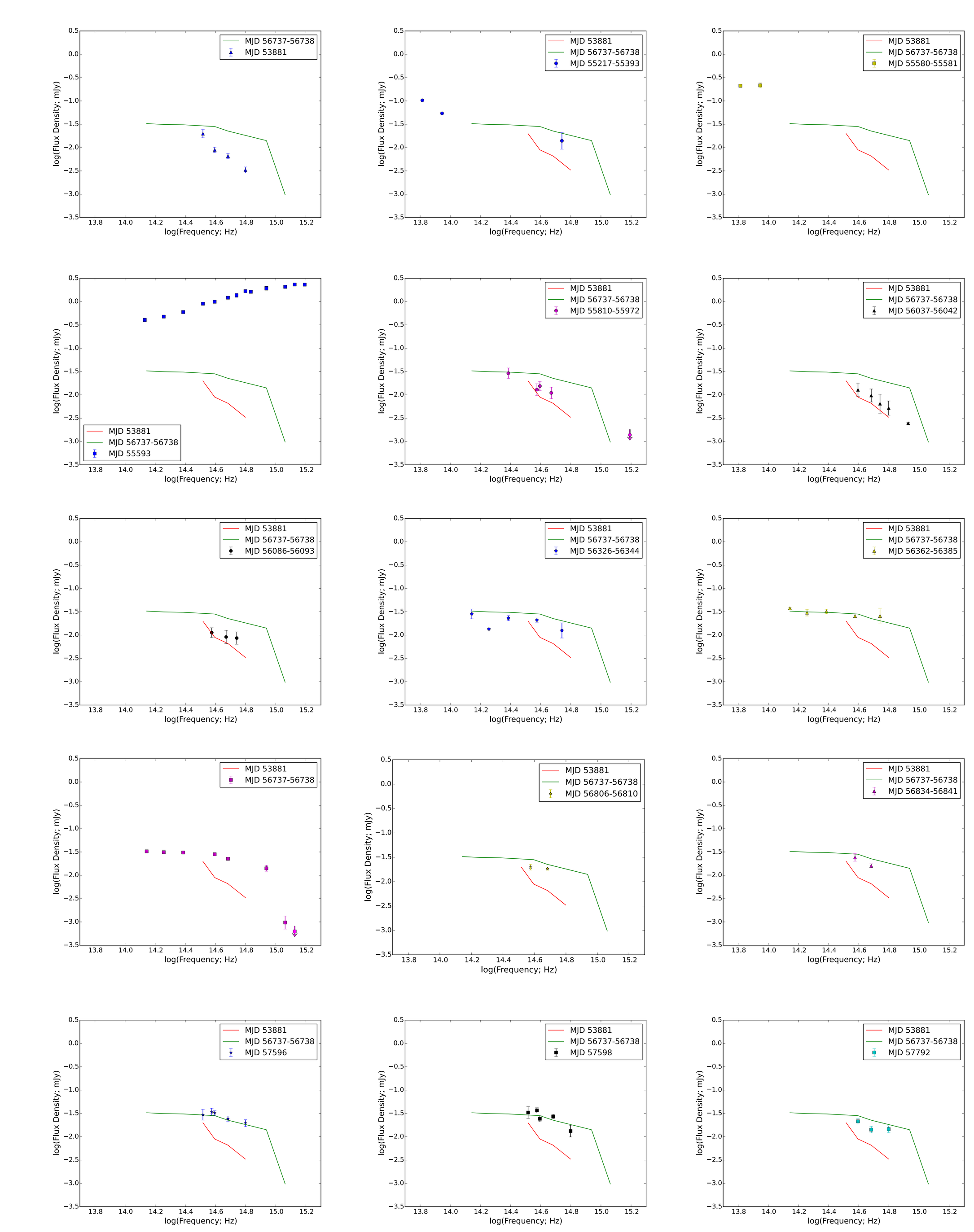


Figure 3. Long-term evolution of the de-reddened flux density (upper panel) and OIR spectral index α, where $F_\nu \sim \nu^\alpha$ (lower panel). Each SED in Fig. 2 is fitted with a single power law and the resulting spectral index is shown here. The two horizontal dotted lines at α = 0 and α = −0.75 represent typical values for optically thick (partially self-absorbed) and optically thin synchrotron spectra, respectively. We find that α varies between ~ −2.5 and 0 in quiescence, with a redder index when the source was faintest.

For the quiescent data after the 2011 outburst, we fit the log(flux density) *I* and *i'*−band light curve (top panel) with a linear function and find a significant rise in flux over the 5.1 years of data. We measure a rise rate of 0.21 ± 0.03 mag/yr (exponential rise in flux, linear rise in magnitude). This rise in quiescence is steeper than any other X-ray binary to date.

SPECTRAL EVOLUTION

Figure 2. OIR SEDs constructed from various date ranges in order to explore the evolution of the SED. All SEDs are from periods of quiescence except MJD 55580–55581 and MJD 55593 which were during the early stages of the 2011 outburst. Each panel has two representative SEDs overlaid in solid lines for comparison, which are from MJD 53881, the SDSS data taken in 2006 in which the source was faint and red, and from MJD 56737–56738, the well-sampled, simultaneous broadband SED presented in Plotkin et al. (2016) when the source was brighter and consistent with a jet spectrum. The evolution of the SEDs allows us to probe variability of the SED shape on timescales longer than the date ranges.



DISCUSSION AND CONCLUSIONS

Swift J1357.2–0933 is a short orbital period (2.8 h), high-inclination BH LMXB that exhibited optical dips during its 2011 outburst due to quasi-periodic obscuration of the accretion flow (Corral-Santana et al. 2013). Since the accretion disc is small and viewed almost edge- on, the disc emission must necessarily be reduced compared to lower inclination and longer period systems. This could explain why in Swift J1357.2–0933 the jet, and not the disc, appears to dominate the OIR emission in quiescence.

We speculate that since the jet luminosity is likely driven by the mass accretion rate in the inner regions of the accretion flow, the relatively fast rise suggests there is an increase in the mass accretion rate onto the black hole preceding the outburst. Such a rise is expected from accretion disc theory (e.g. Lasota 2001), and we observe the steepest rise of any X-ray binary to date. This emphasizes the importance of OIR monitoring of quiescent LMXBs, in particular to identify long-term flux increases that could be the precursor to a forthcoming outburst. The edge-on source Swift J1357.2–0933 is the best example known because of its clear, steep rise, and is also likely the only quiescent source in which the jet properties can be regularly monitored.

REFERENCES

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