
Stable mass transfer from a substellar object onto an M dwarf

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Supplementary Information

Supplementary Discussion. The brown dwarf as accretor Because brown dwarfs and low-mass M dwarfs in this mass range have similar mean densities, either component could in principle fill its Roche lobe at these orbital periods. We therefore also tested the opposite scenario in which the M dwarf fills its Roche lobe and transfers mass onto the brown dwarf. For a grid of brown dwarf accretor masses ($0.04\text{--}0.07 M_{\odot}$, with radii from MESA evolutionary tracks at 5 Gyr), the ballistic stream impacts the brown dwarf on its day side in every case. In this case, peak optical brightness would occur near superior conjunction of the brown dwarf. However, the RV-anchored phase of ZTF J0440+2325 shows that peak brightness occurs near superior conjunction of the M dwarf, strongly indicating that the M dwarf is accreting from the brown dwarf in ZTF J0440+2325. For ZTF J1444+4820, without a detected radial velocity signal this test cannot yet be applied, and the opposite scenario (in which the inner binary hosts an M dwarf donor transferring mass onto a brown dwarf accretor) remains a possibility.

Stability of mass transfer In direct-impact accretion, gas leaving the Roche-lobe-filling donor carries orbital angular momentum and deposits it into the spin of the accretor when it strikes its surface. In the absence of any additional torques, this would spin up the accretor and remove angular momentum from the orbit, leading to runaway orbital inspiral and unstable mass transfer. However, because the spin-orbit synchronization timescale, t_{sync} , scales strongly with orbital separation as $t_{\text{sync}} \propto (a/R)^6$ [1], the tidal torques are expected to be very strong at these close orbital separations (Supplementary Table 1). Thus, even modest deviations from co-rotation are likely rapidly damped by tides. As a result, any angular momentum deposited into the spin of the accretor is likely efficiently transferred back into the orbit through tides, leading to long-lived mass transfer rather than runaway spin-up of the accretor. Furthermore, if the accretor were not synchronously rotating, the impact point of the accretion stream would likely vary significantly, and the light curve morphology would likely change from orbit to orbit. The stable light curves observed over many orbits in both systems are therefore consistent with tidal synchronization of the accretor.

While tides govern the fate of the angular momentum carried by the accretion stream, the stability of mass transfer also depends on how the donor responds to mass loss. Under classical assumptions for conservative mass transfer (e.g., [2, 3]), this response is captured by the adiabatic mass-radius exponent of the donor, $\xi_{\text{ad}} = d \ln R_{\text{don}} / d \ln M_{\text{don}}$. For hydrogen-rich brown dwarfs and fully convective low-mass M dwarfs, $\xi_{\text{ad}} \simeq -1/3$ [3, 4], and the stability criterion of [2] (their Equation 33) simplifies to

$$D = \frac{5}{6} + \frac{\xi_{\text{ad}}}{2} - \frac{M_{\text{don}}}{M_{\text{acc}}}, \quad (1)$$

which requires $M_{\text{don}}/M_{\text{acc}} \lesssim 2/3$ for $D > 0$. Under these assumptions, with the M dwarf as the accretor in both systems, the posterior mass ratios for ZTF J0440+2325 ($q = 0.35^{+0.04}_{-0.03}$) and ZTF J1444+4820 ($q = 0.40^{+0.10}_{-0.06}$) fall below this threshold. We caution that mass-transfer stability cannot in general be reduced to a single critical mass ratio, as the true boundary depends on the donor’s structural response on different timescales, on angular momentum loss, and on how conservative the transfer

is [5–7]. At the very least, however, the inferred mass ratios are not inconsistent with classical stability criteria, and detailed binary evolution modeling will be needed to fully characterize the long-term evolution of mass transfer in these systems.

Lifetime of mass transfer Although the stability of mass transfer is difficult to pin down theoretically, an empirical argument can be made that these systems are experiencing stable and long-lived mass transfer. The most plausible route to Roche-lobe contact in these systems is long-term angular-momentum loss operating over Gyr timescales [8], and very few non-interacting M dwarf–brown dwarf binaries are known at such short orbital periods [8]. It would therefore be unlikely to observe two systems that had only just initiated contact if the ensuing mass-transfer phase were short-lived or rapidly unstable. Given the apparent small progenitor population, a mass-transfer lifetime shorter than $\sim 10^7$ yr would correspond to $< 1\%$ of even a conservative ~ 1 Gyr inspiral timescale (see, e.g., [9] for magnetic braking prescriptions), making it improbable to observe even one such system. We therefore conclude that the mass transfer in ZTF J0440+2325 (and by extension likely ZTF J1444+4820) is probably dynamically stable for at least $\gtrsim 10^7$ yr, and plausibly hundreds of Myr to several Gyr, although more detailed population studies and evolutionary modeling will be necessary to quantify this further.

Compact-object alternatives Because both ZTF J0440+2325 and ZTF J1444+4820 have ultrashort orbital periods and extreme chromatic variability, it is important to consider whether either system could instead host a compact object, such as in a polar or a black widow pulsar, rather than a brown dwarf donor. Although the light-curve morphology of both systems is superficially similar to polars, this interpretation is strongly disfavored by the spectroscopy: neither system shows the cyclotron humps that normally dominate the optical spectra of polars. Furthermore, in both systems, the hot spot has a radius on the order of $R_{\text{hot}} \sim 10^{-2} R_{\odot}$, which is comparable to a typical white dwarf radius and several orders of magnitude larger than the localized accretion spots characteristic of polars [10].

For ZTF J0440+2325, the measured radial velocity semi-amplitude of the M dwarf ($K = 24.7 \pm 2.6 \text{ km s}^{-1}$) also strongly disfavors both the polar and black widow pulsar interpretations. For a circular binary, the semi-amplitude of the visible star is

$$K = \left(\frac{2\pi G}{P} \right)^{1/3} \frac{M_{\text{acc}}}{(M_{\text{acc}} + M_{\text{don}})^{2/3}} \sin i. \quad (2)$$

If the accretor were a $0.6 M_{\odot}$ white dwarf with a $0.083 M_{\odot}$ M dwarf companion, an edge-on binary at $P = 86.65$ minutes would give $K_{\text{edge}} = 420.4 \text{ km s}^{-1}$ for the M dwarf, implying that the observed radial velocity semi-amplitude could only be matched for $i \leq 3.4^\circ$, which has an a priori probability of 1.7×10^{-3} for a randomly oriented system. If the accretor were instead a neutron star, the inclination requirement is even more extreme. For a $1.4 M_{\odot}$ neutron star and a $0.083 M_{\odot}$ companion, the edge-on M dwarf radial velocity at this period would be $K_{\text{edge}} = 585.0 \text{ km s}^{-1}$. This implies that a neutron-star-M dwarf binary would require $i \leq 2.4^\circ$ to match the observed radial velocities of the M dwarf, which has an a priori probability of 8.9×10^{-4} . Furthermore, ZTF J0440+2325 also closely resembles the published object ZTF J1406+1222,

which was previously interpreted as a low-inclination black widow pulsar [11]. Both ZTF J0440+2325 and ZTF J1406+1222 exhibit large-amplitude optical variability, transient Balmer absorption that appears near peak brightness, and unexpectedly small radial velocity semi-amplitudes that are difficult to reconcile with a neutron-star companion. For ZTF J1406+1222, the inclination needed to match the observed radial velocities ($K = 112 \pm 15 \text{ km s}^{-1}$) corresponds to a probability of 1.4×10^{-2} for a $1.4 M_{\odot}$ neutron star and a $0.05 M_{\odot}$ companion. These small radial velocities were originally attributed to a possibly face-on inclination and the low signal-to-noise of the spectra, but a low-mass mass-transferring interpretation offers a more natural explanation (Figure 4 of [11]). In particular, the probability that both ZTF J0440+2325 and ZTF J1406+1222 are independently oriented at such low inclinations is 1.3×10^{-5} , making the black widow explanation highly unlikely. Although the Na I radial velocities of ZTF J1444+4820 show no significant orbital modulation, its optical eclipses rule out a black widow pulsar interpretation, since black widow pulsar optical variability is driven purely by irradiation of the companion.

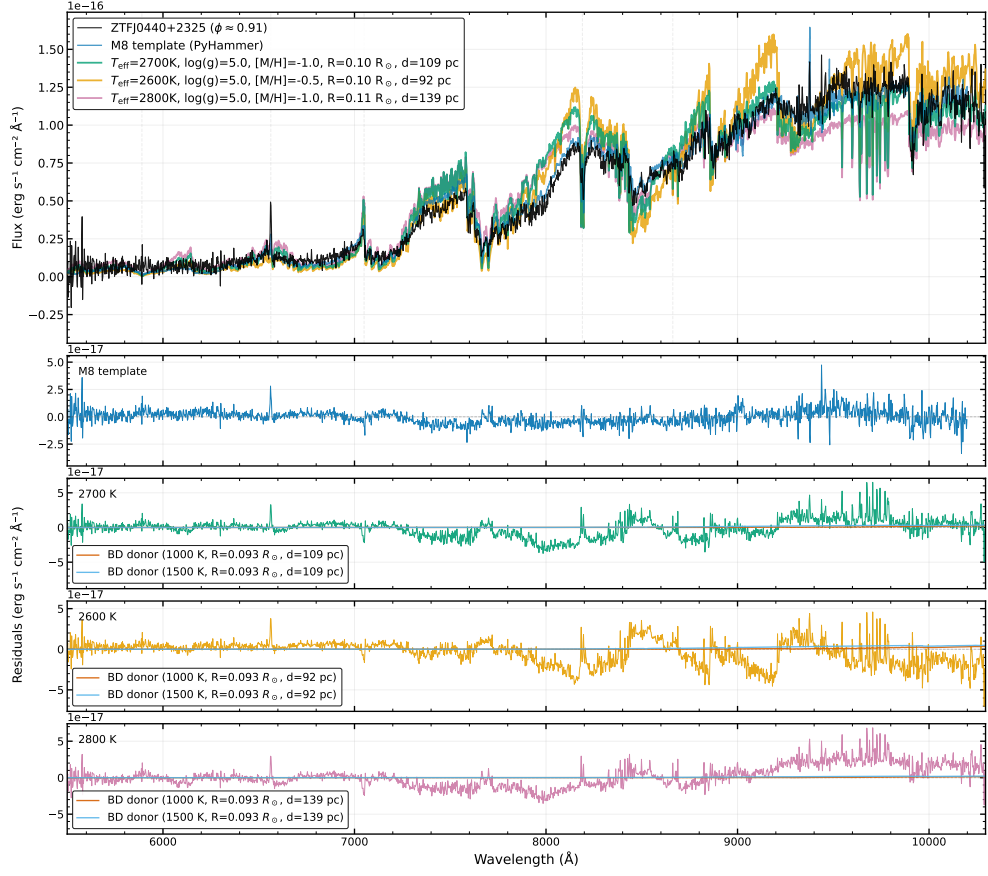
Furthermore, both of these compact-object scenarios also predict strong high-energy emission. Polars typically have X-ray luminosities $L_X \sim 10^{31}\text{--}10^{33} \text{ erg s}^{-1}$ from magnetically funneled accretion shocks [12], while black widow pulsars have $L_X \sim 10^{30}\text{--}10^{32} \text{ erg s}^{-1}$ from intrabinary shocks. Neither ZTF J0440+2325 nor ZTF J1444+4820 is detected by *Swift*, with an upper limit of $L_X < 4.0 \times 10^{29} \text{ erg s}^{-1}$ for ZTF J0440+2325 at 150 pc, below the luminosities of all known polars and nearly all known black widow pulsars. We note that at least one black widow system, PSR J0636+5128, has an X-ray luminosity as low as $L_X \sim 8 \times 10^{29} \text{ erg s}^{-1}$ [13], comparable to the ZTF J0440+2325 upper limit. For ZTF J1444+4820, adopting the geometric distance of 823 pc yields $L_X < 5.7 \times 10^{30} \text{ erg s}^{-1}$, which falls within the range of some black widow pulsars and polars. However, the X-ray constraints are only one of several independent lines of evidence against a compact-object companion in these systems, and in particular the dynamical mass constraint for ZTF J0440+2325 and the optical eclipses of ZTF J1444+4820 each independently rule out a neutron star, while the absence of cyclotron humps in the optical spectra of both systems disfavors a polar.

Size of the hot spots One of the most interesting features of the accretion in these systems is the large size of the hot spots. Although the ballistic accretion stream is expected to impact the accretor over a small localized region (Fig. 2 of the Article), the radii inferred in Methods are of order $R_{\text{hot}} \sim 10^{-2} R_{\odot}$ for both systems. The wavelength-dependent phase of maximum brightness in ZTF J0440+2325 (Fig. 1 of the Article) is also indicative of a large hot spot with a temperature gradient, where the cooler outer regions rotate into view before the hotter regions. Such large hot spots may arise if the thermal energy deposited by the accretion stream is efficiently redistributed (e.g., by strong winds on the accretor). Similar circulation-driven heat redistribution is seen in models of many irradiated atmospheres (e.g., for hot Jupiters [14]), though quantitative modeling of energy transport in direct-impact accretion onto low-mass stars is largely unexplored to date. The inferred hot-spot sizes and wavelength-dependent phase shifts therefore imply that direct-impact accretion onto low-mass stars can produce complex and atypical hot spots that are much larger than

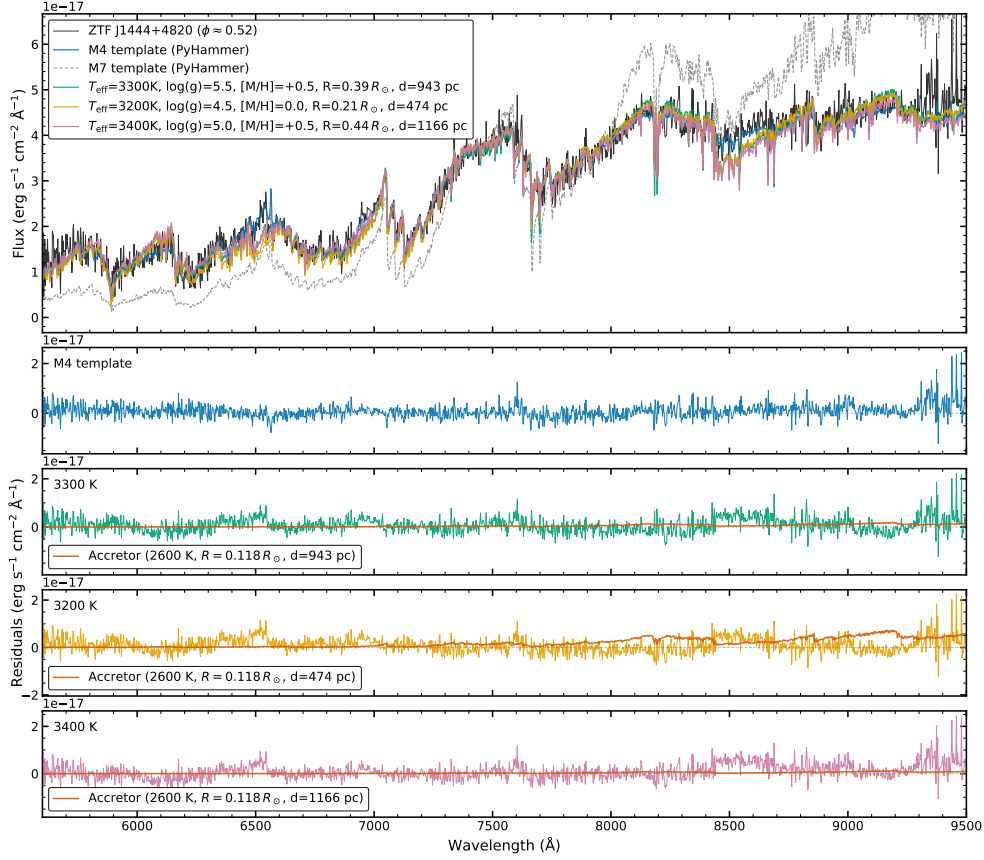
those normally observed (e.g., in white dwarf accretors [\[10\]](#)), pointing to a regime of hot-spot modeling that remains largely unexplored.

Supplementary Table 1 Observational and physical properties of ZTF J1444+4820 and ZTF J0440+2325. The method used to infer each parameter is indicated in parentheses: ZTF = Zwicky Transient Facility; RV = radial velocities; LC = light-curve modeling; MCMC = Roche-geometry MCMC framework; SED/spectral fitting = LRIS fitting; Swift = *Swift*/XRT. All uncertainties represent 68% (1σ) confidence intervals from the MCMC posterior distributions. These uncertainties reflect the statistical posteriors within the adopted physical framework (mass-radius relations, MESA evolutionary tracks) and do not include systematic uncertainties associated with the choice of models. The true error budget is likely dominated by these model-dependent systematics (see Methods). The MCMC-derived parameters for ZTF J1444+4820 assume the inner binary follows the same physical framework as ZTF J0440+2325 and should be treated with caution given the unresolved M4 tertiary.

Parameter	ZTF J1444+4820	ZTF J0440+2325
Right Ascension (deg; ZTF)	221.0388	70.0972
Declination (deg; ZTF)	+48.3456	+23.4264
Orbital period (min; ZTF)	$67.16010 \pm 8 \times 10^{-5}$	$86.6467 \pm 1 \times 10^{-4}$
Accretor mass M_{acc} ($M_{\odot}$; MCMC)	$0.098^{+0.015}_{-0.016}$	$0.083^{+0.005}_{-0.005}$
Accretor mass M_{acc} (M_{Jup})	103^{+16}_{-17}	87^{+5}_{-6}
Accretor radius R_{acc} ($R_{\odot}$)	$0.118^{+0.015}_{-0.016}$	$0.102^{+0.005}_{-0.006}$
Accretor radius R_{acc} (R_{Jup})	$1.15^{+0.15}_{-0.16}$	$1.00^{+0.05}_{-0.05}$
Accretor density ρ_{acc} (g cm^{-3})	83^{+26}_{-17}	109^{+12}_{-9}
Donor mass M_{don} ($M_{\odot}$; MCMC)	$0.0396^{+0.0022}_{-0.0012}$	$0.0287^{+0.0013}_{-0.0008}$
Donor mass M_{don} (M_{Jup})	$41.5^{+2.3}_{-1.3}$	$30.1^{+1.4}_{-0.8}$
Donor radius R_{don} ($R_{\odot}$; MCMC)	$0.0855^{+0.0017}_{-0.0008}$	$0.0907^{+0.0015}_{-0.0007}$
Donor radius R_{don} (R_{Jup})	$0.833^{+0.016}_{-0.008}$	$0.883^{+0.014}_{-0.007}$
Donor density ρ_{don} (g cm^{-3})	$89.2^{+2.2}_{-2.2}$	$54.1^{+1.3}_{-1.3}$
Inclination i (deg; LC / RV+MCMC)	$\gtrsim 75$	$21.6^{+2.5}_{-2.5}$
Age (Gyr; MCMC)	$5.5^{+3.1}_{-3.1}$	$5.5^{+3.0}_{-3.1}$
Semi-major axis a (AU; derived)	$(1.31^{+0.05}_{-0.05}) \times 10^{-3}$	$(1.45^{+0.02}_{-0.02}) \times 10^{-3}$
Roche-lobe radius $R_{L\text{Acc}}$ ($R_{\odot}$; MCMC)	$0.129^{+0.008}_{-0.009}$	$0.147^{+0.004}_{-0.004}$
Roche-lobe radius $R_{L\text{Don}}$ ($R_{\odot}$; MCMC)	$0.0855^{+0.0017}_{-0.0009}$	$0.0907^{+0.0015}_{-0.0009}$
Accretor filling factor $R_{\text{acc}}/R_{L\text{Acc}}$ (MCMC)	$0.917^{+0.058}_{-0.066}$	$0.697^{+0.017}_{-0.019}$
Donor filling factor $R_{\text{don}}/R_{L\text{Don}}$ (MCMC)	$1.000^{+0.008}_{-0.008}$	$1.000^{+0.008}_{-0.008}$
Density ratio $\rho_{\text{acc}}/\rho_{\text{don}}$	$0.93^{+0.31}_{-0.19}$	$2.01^{+0.22}_{-0.18}$
M dwarf RV semi-amplitude K (km s^{-1} ; RV)	—	24.7 ± 2.6
Minimum companion mass $M_{\text{don}} \sin i$ (M_{Jup} ; RV)	—	9.7 ± 1.2
Distance (pc; SED/spectral fitting)	—	$\sim 100\text{--}150$
distance (pc; Gaia EDR3 geometric)	823 (574–1304)	—
X-ray luminosity L_X (erg s^{-1} ; Swift)	$< 5.7 \times 10^{30}$ (3σ) at 823 pc	$< 4.0 \times 10^{29}$ (3σ) at 150 pc

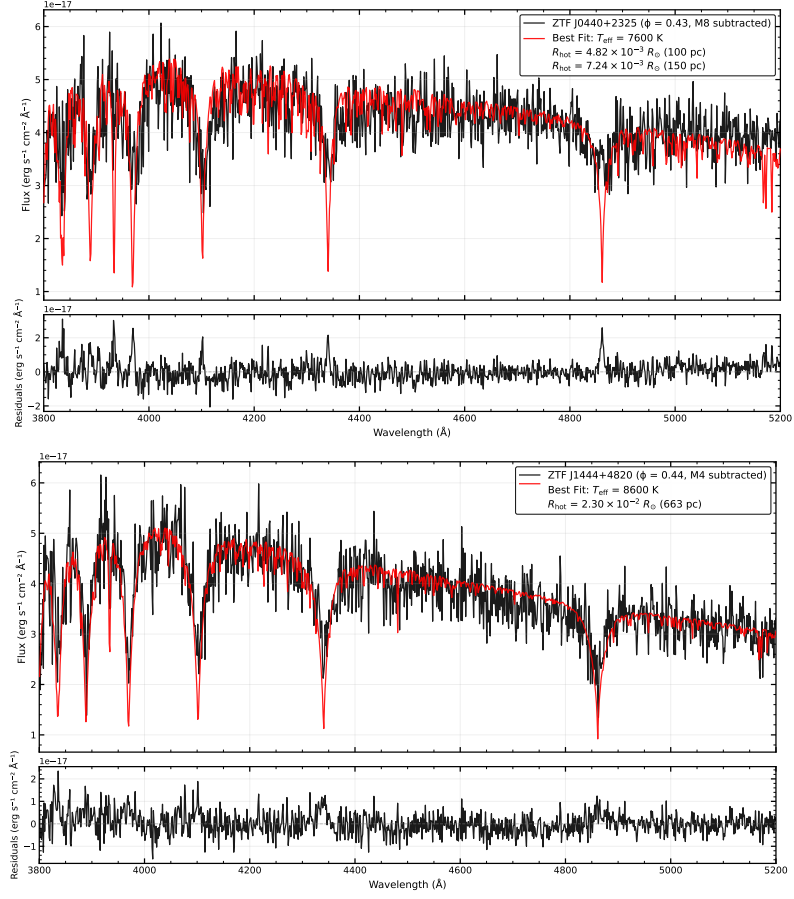


Supplementary Figure 1 Atmosphere model fits for ZTF J0440+2325. In the top panel, a flux-calibrated Keck/LRIS optical spectrum obtained near minimum brightness (black) is compared to an empirical M8 dwarf template and BT-Settl atmosphere models (colored lines). The BT-Settl fits imply a photometric distance of approximately 100–150 pc. Residuals are shown below each fit. In the BT-Settl residual panels, the predicted flux contribution of the brown dwarf donor is overlaid for $T_{\text{eff}} = 1000\text{ K}$ and 1500 K BT-Settl models, scaled to the MCMC donor radius (Supplementary Table 1) and the photometric distance of each fit. The donor flux falls below the model-data residuals at optical wavelengths.



Supplementary Figure 2 Atmosphere model fits for the M4 tertiary in ZTF J1444+4820.

(a) A flux-calibrated Keck/LRIS red-arm spectrum obtained near minimum brightness compared to an empirical M4 dwarf template (blue), an M7 dwarf template (gray dashed, for comparison), and the three best-fitting BT-Settl atmosphere models (colored lines). Residuals (observed minus model) are shown for the M4 template and each BT-Settl model. In the BT-Settl residual panels, the predicted flux contribution of a potential M dwarf accretor in the inner binary is overlaid for a $T_{\text{eff}} = 2600$ K BT-Settl model scaled to the MCMC accretor radius ($R_{\text{acc}} = 0.118 R_{\odot}$, Supplementary Table 1) and the distance implied by each model fit. This predicted flux falls below the model-data residuals at the larger distances and remains comparable to the residual scatter for the smallest-distance model.



Supplementary Figure 3 Hot-spot temperature constraints. Blue-arm spectra obtained near peak brightness, after subtracting the scaled M dwarf templates, compared to BT–Settl atmosphere models. The best-fitting models imply hot-spot temperatures of ~ 7600 K for ZTF J0440+2325 and ~ 8600 K for ZTF J1444+4820. Residuals are shown below each fit.

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