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Optical Properties of Quasars that have rapidly Rising and Falling Infrared flux

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ABSTRACT
"Changing-look" quasars (CLQs) vary much faster than expected from classic, thin, Shakura-Sunyaev accretion disks. Our team has recently demonstrated that infrared-selected CLQs allow us to probe the very central regions of quasars, including the innermost stable circular orbit (ISCO) and potentially test predictions of General Relativity. We have extracted a set of 21 IR-selected CLQs from the SDSS using new data from the NEOWISE-R mission. These objects have striking falling and rising mid-IR fluxes, but have representative SDSS spectra from ≈6 to 14 years ago (rest-frame). We propose the first systematic study of IR-selected CLQs and request 2 dark nights in order to reveal the recent optical spectral state of these quasars. Our baseline expectation is that WHT spectra of the IR Risers (Faders) will show hotter, bluer (cooler, redder) disks with larger (smaller) EW broad lines than seen with SDSS. Likewise, WHT optical spectra of the IR Faders will show cooler, redder disks with smaller EW broad lines than seen by SDSS. Any departure from this expectation will further inform us how the classical model breaks down.

Key words: keyword1 – keyword2 – keyword3

1 INTRODUCTION

"Changing-look" quasars (CLQs) vary much faster than expected from classic, thin, Shakura-Sunyaev accretion disks, and lead to the current situation that has been dubbed the "Quasar viscosity crisis" where the CLQs have broken standard viscous accretion disk models (e.g. Lawrence 2018; Antonucci 2018). Infrared (IR) observations allow us to rule out obscuration as a cause of the extreme variability. As we showed in Ross et al. (2018) and Stern et al. (2018), optical variability of IR-selected CLQs is so fast and of such large amplitude that the driver is most likely changes in a puffed-up, viscous inner accretion disk, close to the innermost stable circular orbit (ISCO).

As a result, IR-selected CLQs (Graham et al. 2019) allow us to probe the innermost regions of quasars, including the ISCO, the plunging region and to investigate predictions of General Relativity in strong gravity. The role of IR-selection is key to revealing these powerful probes of disks and spacetime close to the black hole.

Although extreme IR variability rules out the dust obscuration scenario for the currently discovered CLQs, understanding what the *hot dust* does, on the outer, or indeed maybe even overlapping, edge of the BLR is crucial to understanding how central engines work and how their photon and energy budget propagate to the nuclear galactic regions.

IR emission from quasars is widely believed to be produced in dusty gas by reprocessed continuum UV emission. We have extracted a set of $z \approx 0.3$ quasars that exhibit striking 'falling' (Fig. 1; top) and 'rising' (Fig. 1; bottom) mid-IR fluxes over a period of ≈4 years. In each case we have representative SDSS spectra (see Fig. 2) from before this fade/rise and we have established that these objects are not blazars by removing objects that would fulfil a traditional "radio loud" criterion.

WHT spectra of these quasars will allow us to carry out a simple test of the IR "Risers" and "Faders". Since IR emission is reprocessed continuum emission from the disk, our baseline expectation (null hypothesis) is that WHT spectra of the "Risers" will show hotter, bluer disks with larger EW broad lines than seen with SDSS. Likewise, WHT optical spectra of the "Faders" will show cooler, redder disks with smaller EW broad lines than seen by SDSS. Measuring the EW in both states is good test for SED changes where we need a larger sample than currently available to not be limited statistically. Here we propose the first ever systematic study of IR-selected CLQs. We request two dark nights in order to reveal the optical spectral properties of these quasars.

Crucially, we have first epoch spectral data from SDSS, and thus can perform an "absolute" (i.e. 1st epoch vs. 2nd epoch) measurement as well as a "relative" (2nd epoch Risers vs. 2nd epoch Faders) test. By comparing the disk luminosity between the 1st epoch SDSS spectra and the 2nd epoch WHT spectra we will be able to constrain the change in the accretion rate and inner disk temperature for each quasar. This difference should be directly comparable to the magnitude of IR rise or fall in that quasar between epochs. Thus, we have a strict and simple null hypothesis test. A confirma-

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tion of the null hypothesis in our sample gives us some confidence that IR-selection of CLQs is probing what we think it should, i.e. dusty gas beyond the regular broadline region. Any departure from the null hypothesis reveals a flaw in our simple expectations and a flaw in the IR-selection criterion of CLQs. It will provide grounds for both follow-up theoretical work and follow-up observations on a larger sample of risers and faders. The latter will test the rate of departure from our null hypothesis for CLQs.

As such, even if we do not observe any significant differences in the second spectral epoch to the first, this is interesting due to the dramatic differences in the associated infrared fluxes. Moreover, it is currently unknown whether there are any fundamental differences between quasars that show an increase in the MIR flux compared to those that show a decrease.

Our sample spans a period of ≈6-14 years in the rest-frame since the SDSS spectra were obtained, see Figure 3, and these objects also generally have Eddington ratios $\approx 1\% - 10\%$. Calculating if there has been an increase/decrease in the Eddington ratio in 2019A will again give key insights on the mechanisms powering extremely variable quasars.

If our hypothesis is supported by the data, we will be able to quantify the expected variability in the IR due to optical continuum changes. This will enable us to further investigate the relationship between the optical continuum source and the IR source in AGN, and, in particular how changes of the innermost accretion disk (near the ISCO) impact AGN structures at parsec (and perhaps larger) scales.

Finally, we note that obtaining time-domain spectroscopy for IR-variable quasars, links directly to the WEAVE science case and observations of radio AGN and galaxies in the medium deep LOFAR surveys and quasars detected in ESA *Gaia*.

2 SAMPLE SELECTION AND OBSERVATIONS

2.1 IR CLQ Sample Selection

We selected 23 quasar known quasars with interesting rising or falling mid-infrared light curves, for new spectroscopic observartions.

Sample construction. Our superset of data is the SDSS DR14 Quasar Catalog (hereafter, "DR14Q"; Pâris et al. 2018). We first limit the sample to $0.25 \leq z \leq 0.35$ in order to access Mg II , Hβ and Hα (in WHT/ISIS spectra). For this redshift range, WISE W1 (W2) accesses rest-frame 2.52-2.72 (3.33-3.60) μm, so still corresponding to hot dust. Limit to Decl. $\delta \leq +20$ deg to enable follow-up from Southern Hemisphere; sample drops to 1233 quasars. 1.20 airmass... Obtain the NEOWISE-R 2018DR light curves, and apply additional requirement that $w1snr > 2$ for individual L1b frames; sample drops to 1219 quasars. Visually inspect all 1219 NEOWISE-R light curves for interesting objects (i.e., quasars with obviously rising or fading NEOWISE-R light curves) and concentrate on objects with $120 < R.A./deg < 250$ for 2019A. This yields a sample of 23 objects (17 "Faders", 6 "Risers").

We check for blazars via the CRATES Flat-Spectrum Radio Source Catalog (heasarc.gsfc.nasa.gov/W3Browse/radio-catalog/crates.html), finding no matches. We also checked with VLA FIRST Catalog Database (2014dec17) and removed two objects, one with a FIRST detection, and one radio-undetected source that might fit the radio-to-optical flux ratio definition of radio-loud (e.g., Stern et al., 2000, AJ, 132, 1526) given its faint optical magnitude. **We arrive at a sample of 23 objects with xx of these being "Faders" and yy being "Risers".** Our target list is given in Table 1.

2.2 Observational Details

Observing Notes: The second epoch of spectroscopy for the Riser/Fader IR quasars was obtained from the 4.2m William Herschel Telescope at the Roque de Los Muchachos Observatory on La Palma on the nights of the 28th and 29th June 2019 (MJDs 58663 and 58664). The Intermediate-dispersion Spectrograph and Imaging System (ISIS) instrument was used. Each target had a single science exposure of 1800 seconds. The Red grating was R158R, the Blue Grating R300B. The D5300 dichroic was used along with the Red Filter GG495, a central red wavelength of 7500 Å and a central blue wavelength of 4500 ÅThe chip binning was 2 1 (i.e. 2× binning in the spatial direction), with a standard window and 1.00" slit width. Given these exposure times and the general very good (clear, Dark, seeing 0.3-0.6") conditions. (1.00" seeing, 1.20 airmass,, Dark time) we achieve a SNR of $\approx xx - yy$ /pixel for all our targets.

The resolution achieved by WHT/ISIS is... so that the broadlines are well resolved, and ideally so that the narrow lines (width ∼ 500 km/s) are at least marginally resolved. We use grating R300B in the blue arm, with 0.86Å/pixel, and with a 1″ slit giving resolution 3.4Å, equivalent to velocity resolution of 200km/s at 5200Å. With the red arm we use R158R which gives a similar velocity resolution at 7000Å. This combination gives complete wavelength coverage with reasonable resolution.

2.3 Data Reduction

Make sure to cross-check with MacLeod et al. 2019 full list of 262 candidates...

3 RESULTS

Our key observational results are presented in Figure x.

3.1 Maths

Simple mathematics can be inserted into the flow of the text e.g. $2 \times 3 = 6$ or $v = 220\,\mathrm{km\,s^{-1}}$, but more complicated expressions should be entered as a numbered equation:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}. \tag{1}$$

Refer back to them as e.g. equation (1).

3.2 Figures and tables

Figures and tables should be placed at logical positions in the text. Don't worry about the exact layout, which will be handled by the publishers.

Figures are referred to as e.g. Fig. 3, and tables as e.g. Table 2.

3.3 Disk Emitters

cf. our objects with e.g. Figure 11 Shen et al. (2011) and J161742.53+322234.3. Are any of the WHT CLQs Shen "Disk Emitters" ("bit # 1 set = disk emitter candidates;")

Object Name	R.A.	Decl.	redshift	SDSS MJD	WHT night	Notes
J1348+2456	207.092999671	+24.947260777	0.293	53535	2nd	ROSAT source
J1555+2119	238.834080827	+21.320782052	0.289	53557	2nd	Host seen in SDSS image
J1600+3345	240.013675832	+33.762683980	0.349	53142	2nd	
J1601+4745	240.296914145	+47.752692667	0.297	52354	1st	
J1603+1531	240.759453240	+15.532625448	0.346	53555	2nd	
J1605+4834	241.283014512	+48.572815722	0.294	52054	1st	
J1605+2309	241.39222	23.16390	0.316	53524	1st	
J1610+1525	242.631737970	15.427023939	0.301	53918	1st	
J1615+2507	243.910890725	+25.122351270	0.284	53493	2nd	ROSAT source
J1632+2403	248.238039021	24.055350336	0.310	53177	1st	
J1634+1118	248.712924199	+11.313665524	0.294	54585	1st	
J1704+3331	256.104645878	+33.529446263	0.290	5x	1st	
J1709+3421	257.494827595	+34.358145781	0.294	5x	1st	
J1713+2736	258.474381047	+27.607453430	0.298	52410	2nd	**?**
J2102-0645	315.535560174	-6.750523111	0.325	52174	2nd	
J2222+1733	335.605032422	17.560893866	0.289	56944	1st	
J2223+2101	335.867533233	21.024051645	0.307	56960	1st	
J2232-0806	338.043832196	-8.105930411	0.276	—	2nd	"Big Dipper"; **?**
J2251+2419	342.927673403	+24.320710413	0.305	56238	2nd	BOSS galaxy group
J2256+1450	344.049258991	14.849886560	0.251	52263	1st	ROSAT source
J2307+1901	346.940122238	+19.022347710	0.313	56946	2nds	SPIDERS target
J2320+2305	350.210471865	+23.088347026	0.283	56535	2nd	Very close companion star
J2322+2235	350.739803201	+22.591362824	0.292	56977	2nd	SPIDERS target

Table 1.

Table 2. This is an example table. Captions appear above each table. Remember to define the quantities, symbols and units used.

A	B	C	D
1	2	3	4
2	4	6	8
3	5	7	9

4 DISCUSSION

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5 CONCLUSIONS

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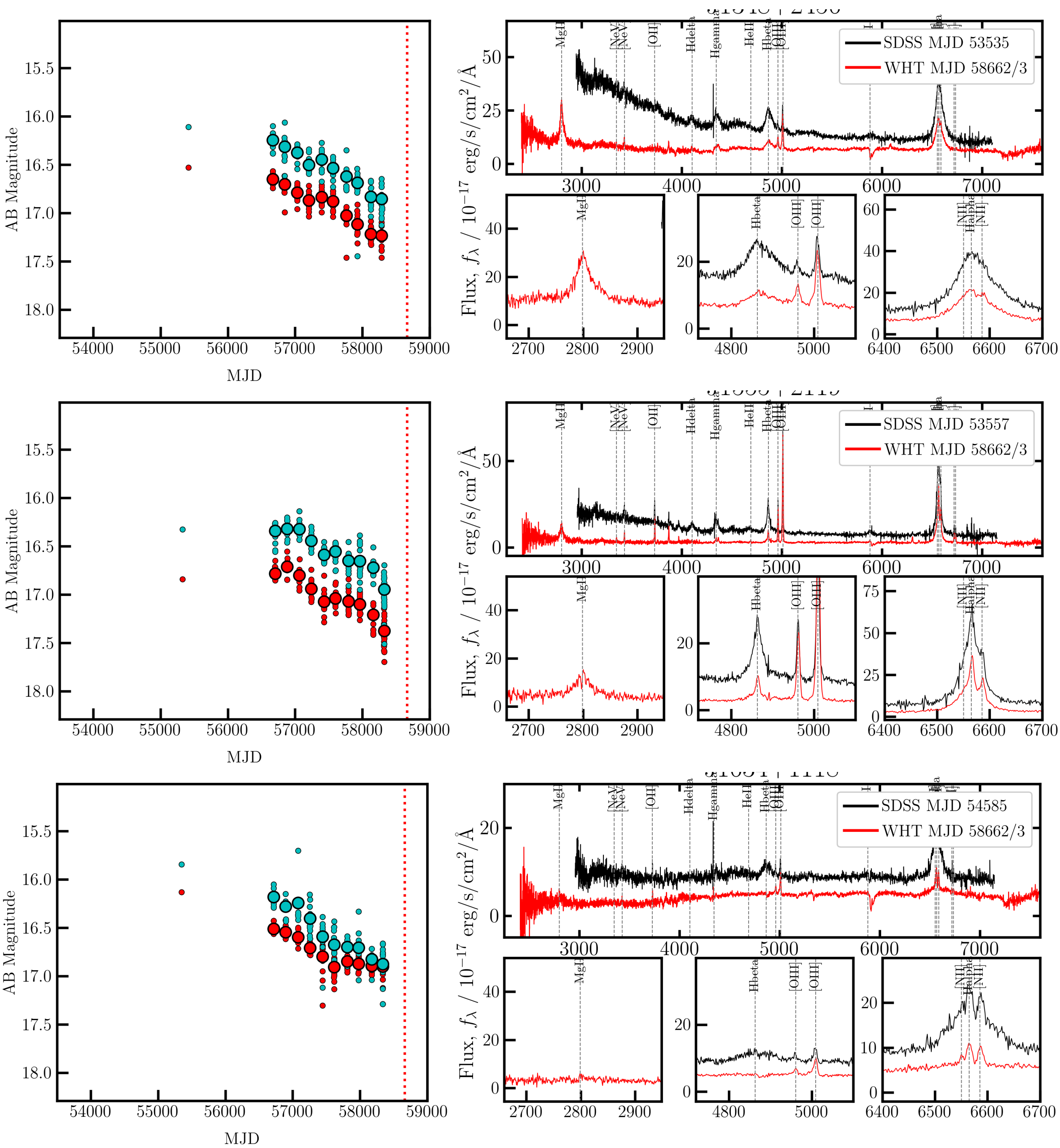

Figure 1.

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ACKNOWLEDGEMENTS

The Acknowledgements section is not numbered. Here you can thank helpful colleagues, acknowledge funding agencies, telescopes and facilities used etc. Try to keep it short.

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Shen Y., et al., 2011, ApJS, 194, 45

Stern D., et al., 2018, ApJ, submitted

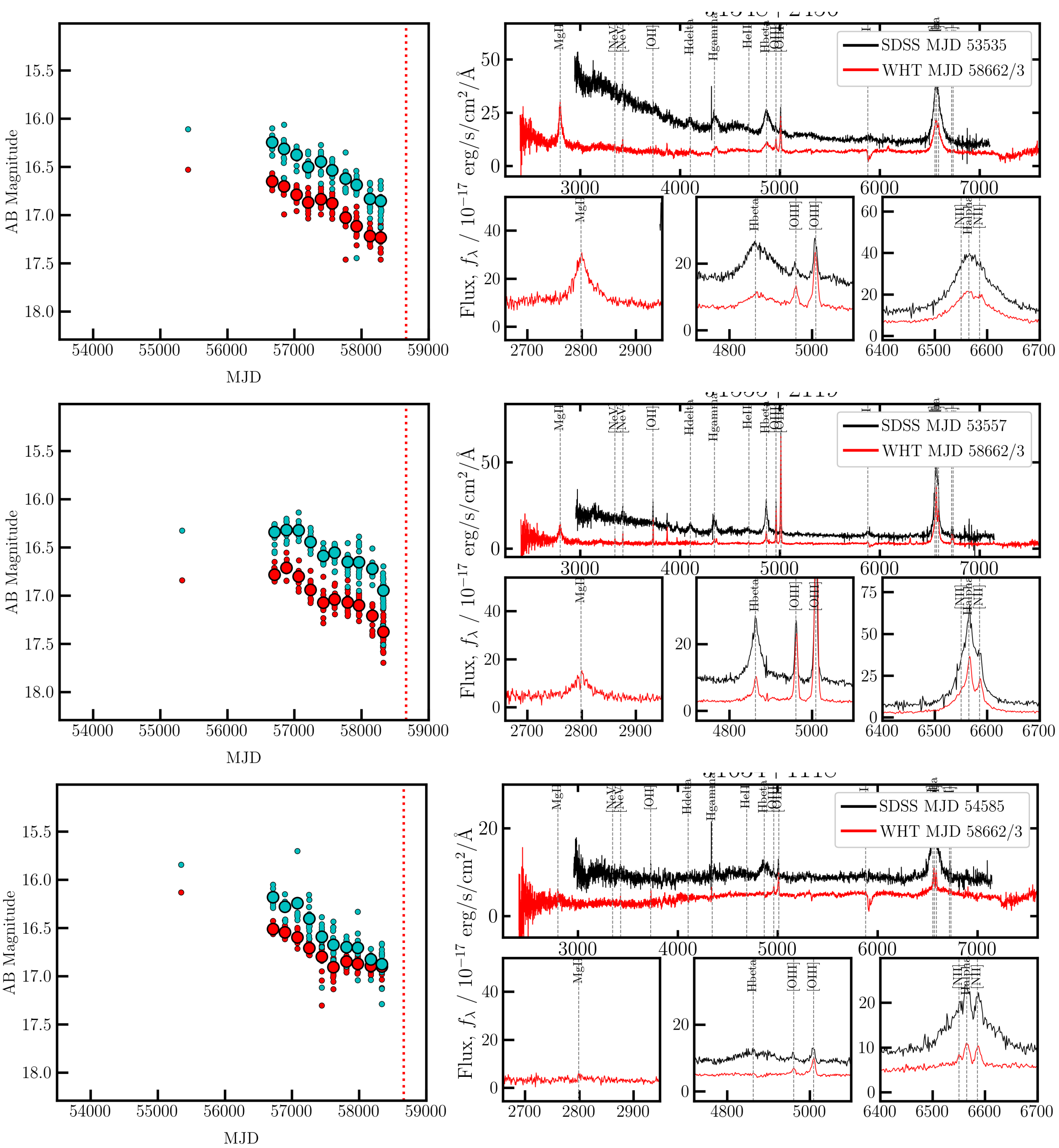

Figure 2.

APPENDIX A: SOME EXTRA MATERIAL

If you want to present additional material which would interrupt the flow of the main paper, it can be placed in an Appendix which appears after the list of references.

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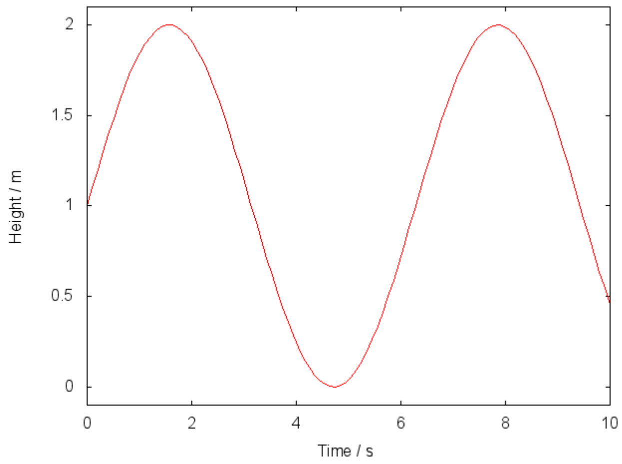

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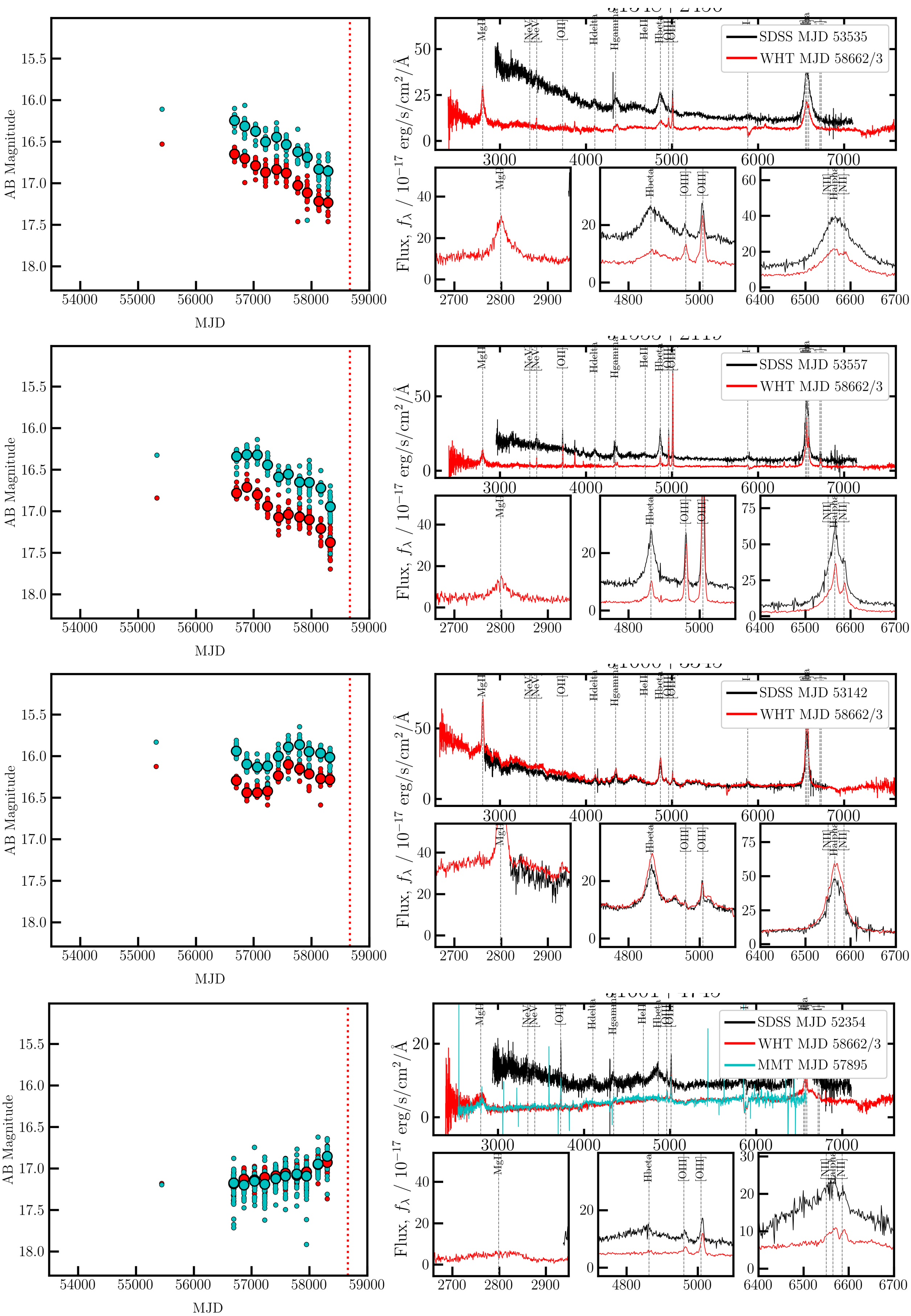
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WHT MJD 58662/3
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MMT MJD 57895
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Figure A1.

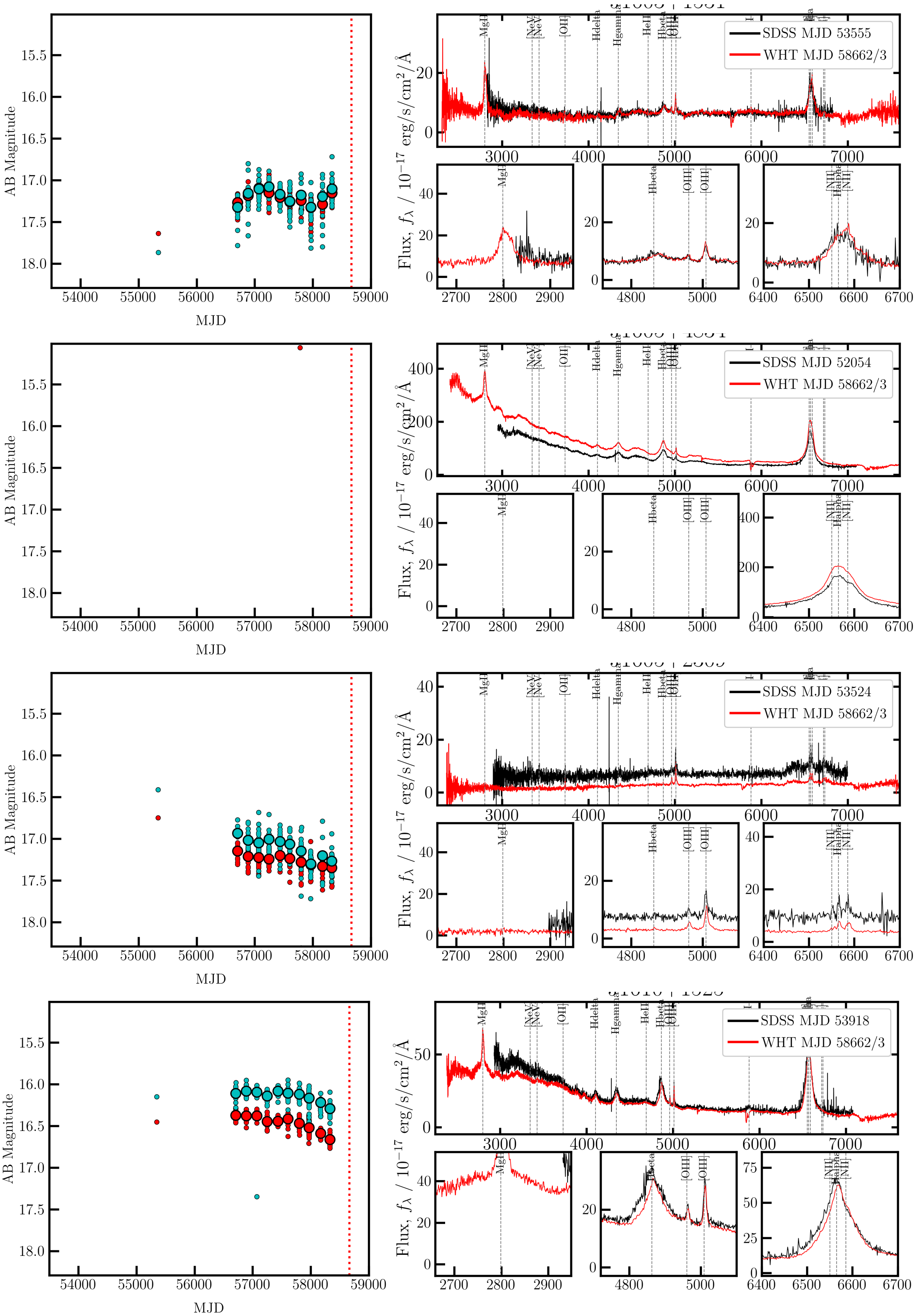
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Figure A2.

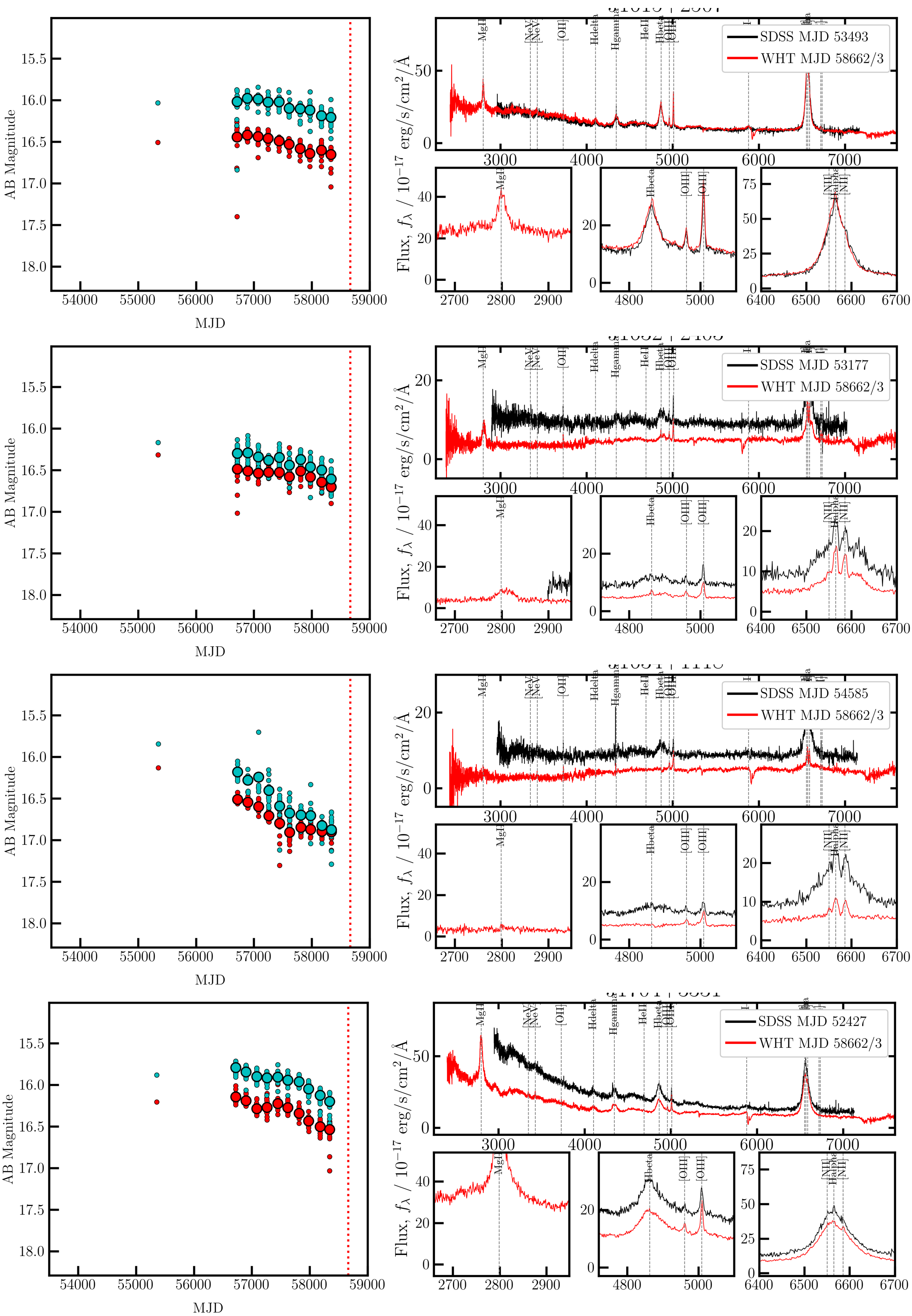
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Figure A3.

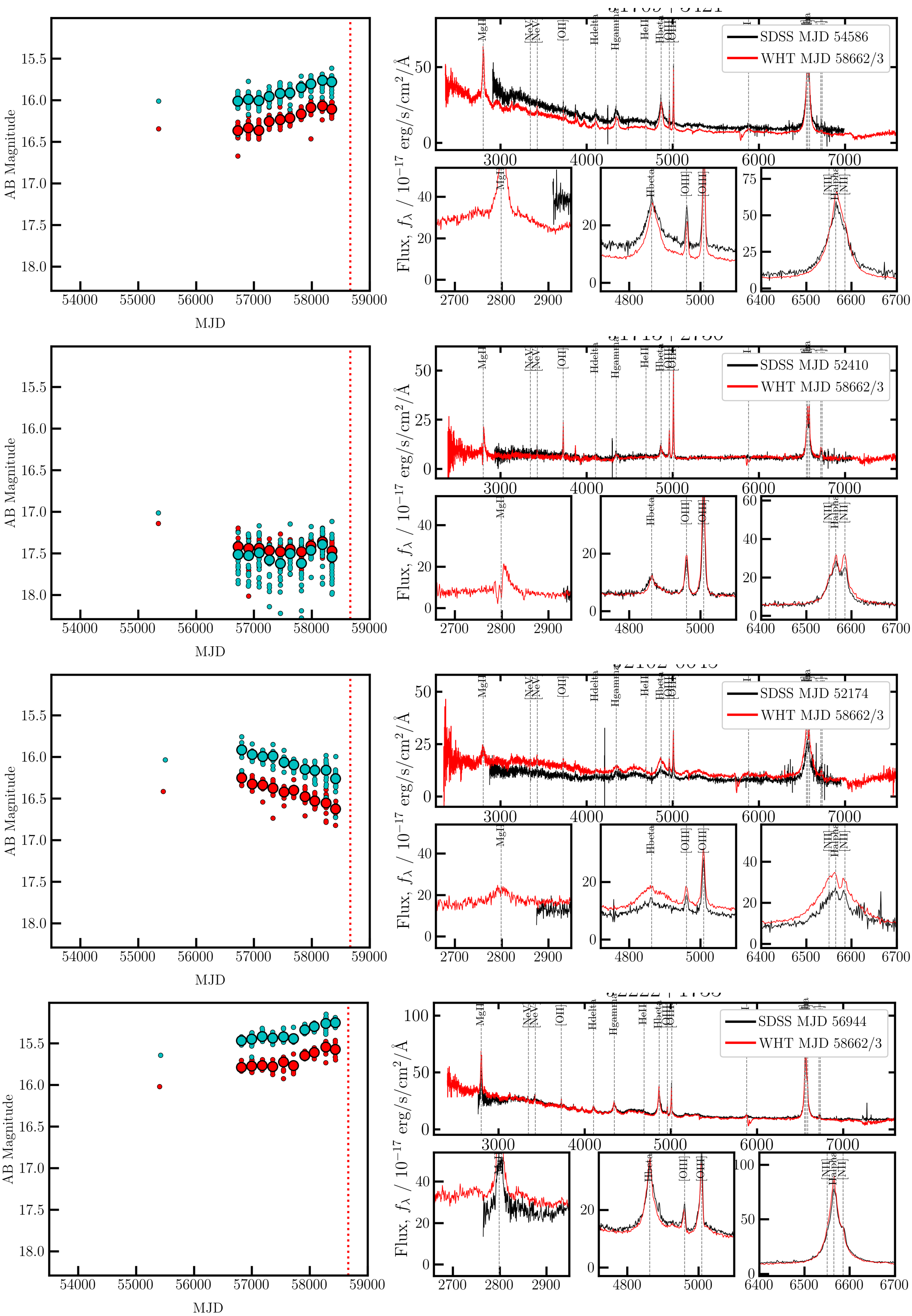
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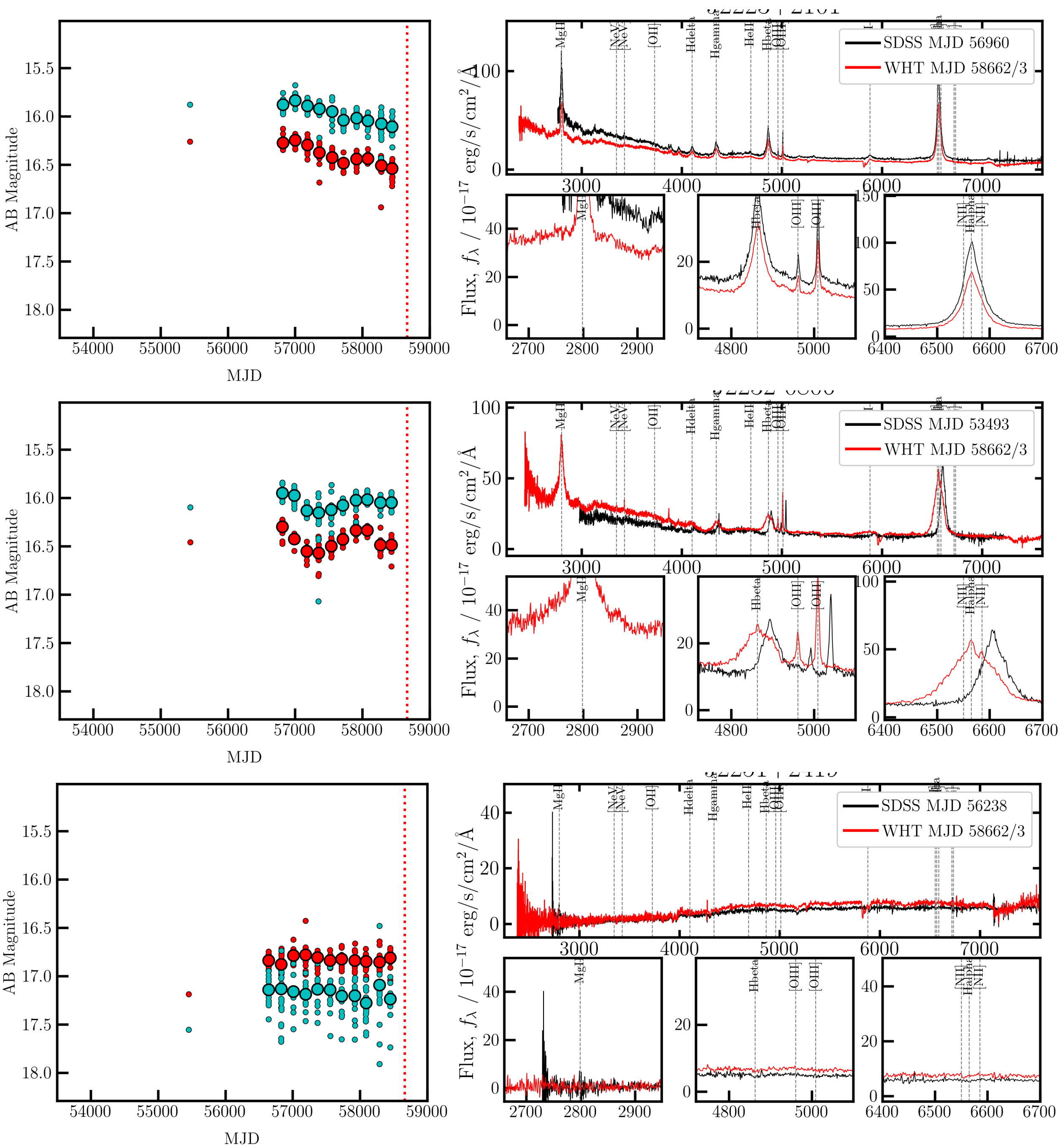
Figure A4.



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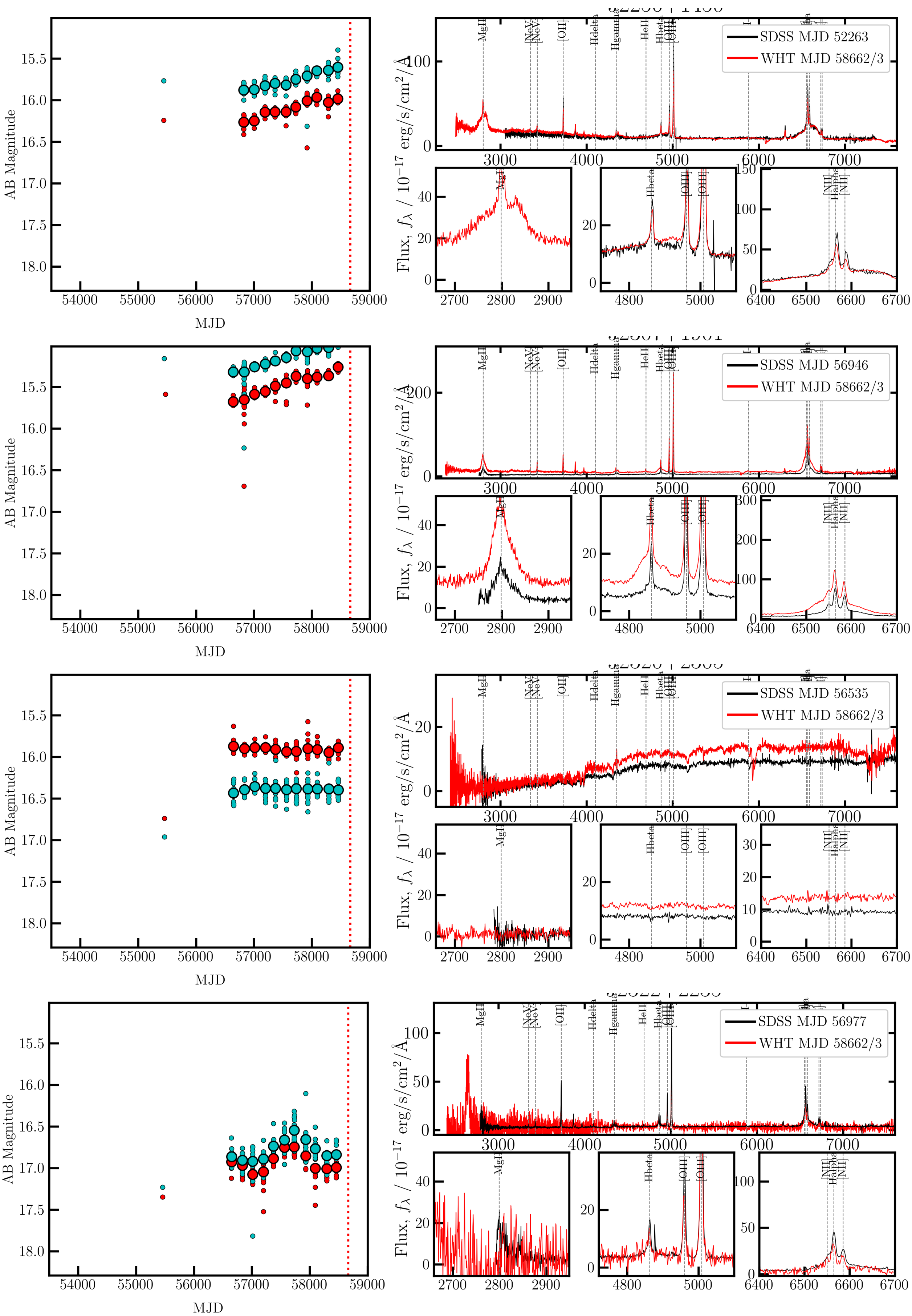

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