ASTR 5110 Atomic and Molecular Processes Fall 2022. Problem Set 10. Due Wed 9 Nov.

1. An unusual N III fluorescence line from an accreting supermassive black hole

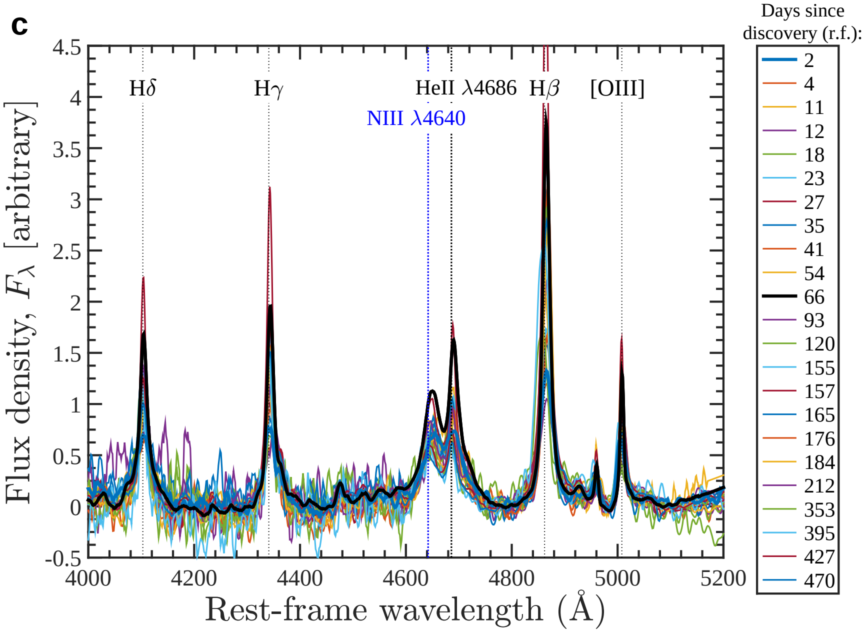

Figure 1: Optical spectrum of the accretion event AT 2017bgt on to a supermassive black hole over a period of 470 days (Trakhtenbrot et al. 2019 https://arxiv.org/abs/1901.03731).

Trakhtenbrot et al. (2019) https://arxiv.org/abs/1901.03731 report that the All Sky Automated Survey for Supernovae observed the early-type galaxy 2MASX J16110570+0234002 at $z = 0.064$ to brighten significantly over a two month period in 2017, an event they dubbed AT 2017bgt. The brightening did not match the lightcurve of a supernova, but was more similar to a TDE (Tidal Disruption Event), in which a supermassive black hole tidally disrupts a passing star, and proceeds to accrete the remains over a period of a year. Observations with the SWIFT, NuSTAR, and NICER satellites shortly after discovery established that AT 2017bgt had brightened in the ultra-violet by the exceptionally large factor of 75, and in x-rays by a factor of ~ 2–3. Optical spectroscopy, Figure 1, showed that, unusually for a TDE, the optical brightness remained roughly constant for more than a year. The spectrum also showed an unusual emission line which Trakhtenbrot et al. identify as N III $2s^2 3p\ {}^2P - 2s^2 3d\ {}^2D$ 464 nm, which they argue is a fluorescence line that results from a cascade of allowed lines after He II Lyα pumps N III in its ground state to a high lying level.

(a) The resonance line (allowed line connecting to the ground state) that is pumped by He II Lyα 30.3786 nm is N III $2s^2 2p\ {}^2P_{1/2} - 2s2p3p\ {}^2S_{1/2}$ 30.5756 nm. Would N III have to be redshifted or blueshifted, and by how much, in km/s, to make that resonance line coincident with the He II Lyα line? Is that velocity plausible, given the width of the allowed lines in the observed spectrum Figure 1?

(b) As a simplified model of fluorescence, consider a 3-level atom (of N III). Assume that the 3 levels are populated by radiative pumping by He II Lyα at rate W_{13} and stimulated emission at rate W_{31}, and by allowed radiative decays, so

$$\dot{n}_1 = -n_1 W_{13} + n_2 A_{21} + n_3 (A_{31} + W_{31}) \ , \tag{1a}$$
$$\dot{n}_2 = -n_2 A_{21} + n_3 A_{32} \ , \tag{1b}$$
$$\dot{n}_3 = -n_3 (A_{31} + W_{31} + A_{32}) + n_1 W_{13} \ . \tag{1c}$$

Show that in steady state

$$n_1 : n_2 : n_3 = 1 : \frac{W_{13} A_{32}}{A_{21}(A_{31} + W_{31} + A_{32})} : \frac{W_{13}}{A_{31} + W_{31} + A_{32}} \ . \tag{2}$$

(c) Use detailed balance to argue that in thermodynamic equilibrium at temperature T_{13}, the rates of radiative decay A_{31}, excitation W_{13}, and stimulated decay W_{31} are related by

$$\frac{g_3 A_{31}}{e^{h\nu_{13}/kT_{13}} - 1} = g_1 W_{13} = g_3 W_{31} \ . \tag{3}$$

The temperature T_{13} is called the excitation temperature of the line.

(d) What is the energy $h\nu_{13}/k$ of the He II Lyα line in Kelvin? Argue that the excitation temperature T_{13} of the 1 and 3 levels of N III cannot exceed the temperature of a hypothetical blackbody source centered on the supermassive black hole.

(e) The condition for a laser is that there be a population inversion $n_U/n_L > g_U/g_L$. Could the 1 ↔ 3 transition develop a laser? Could the 2 ↔ 3 or 2 ↔ 1 transitions perhaps develop a laser?

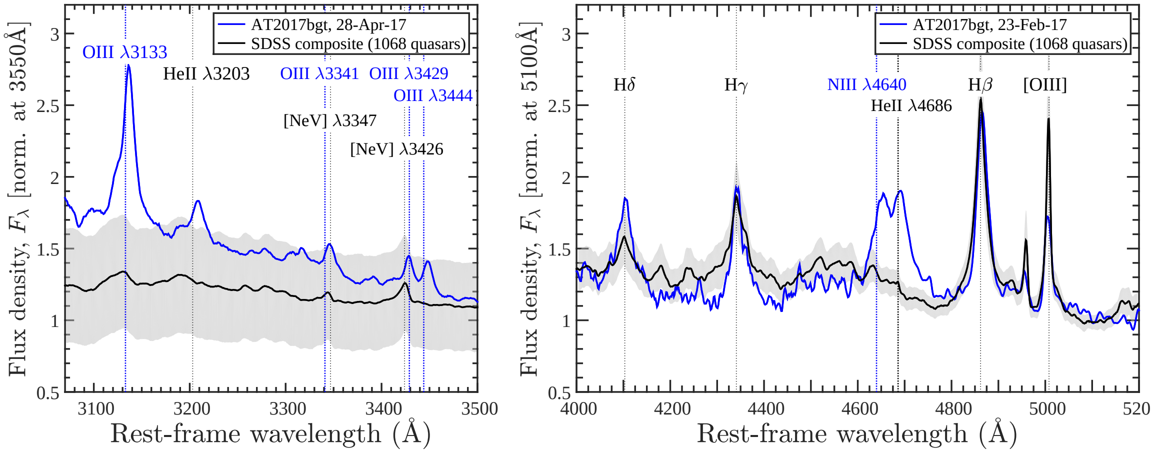

Figure 2: Near UV and optical spectrum of AT 2017bgt two days after discovery, compared to a composite of SDSS quasars. The spectrum of AT 2017bgt shows fluorescence lines, notably O III 313 nm and N III 464 nm, that are atypical of quasars.