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Emission Lines in Astrophysics

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Summary. A brief review is presented on the astrophysical sites that produce optical emission lines and useful information the emission lines provide on physical processes at such sites. Examples of emission line spectra are presented based on observations made with the Himalayan Faint Object Spectrograph on the 2-m Himalayan Chandra Telescope, Indian Astronomical Observatory, Hanle. Basic principles involved in modeling emission line fluxes are listed.

1 Introduction

Emission lines are ubiquitous in astrophysics, and indicate the presence of ionized or excited gas. They arise in outer layers of Sun and stars, immediate environments of stars (circumstellar region) and in the interstellar gas. Their importance lies in the simplicity of physical processes that give rise to the emission, especially in the case of diffuse matter, which can be used to deduce the physical conditions such as the electron temperature and density, and relative abundances of species in which the electronic transitions take place. In addition, the doppler shifts of emission lines are widely used to infer kinematic information such as the recession velocity of galaxies, their internal kinematics, as also rotation or expansion velocities in circumstellar environment. Observationally, the emission lines are also easier to detect since they stand out above the fainter continuum level.

2 Physical Processes

Osterbrock & Ferland (2005) is an excellent text book for the study of astrophysics of gaseous nebulae and active galactic nuclei. The processes that operate in these two kinds of objects are applicable with minor differences in diverse kind of astrophysical situations. They involve ionization and excitation of gas around stars and other compact objects which may be diffuse, in an accretion disk, or ejected in bipolar jets perpendicular to the accretion disk.

The most important processes in emission-line regions are listed below with the most common example for each process.

1. Photoionization — for example,
   $\mathrm{H} + h\nu(\lambda < 912\mathrm{nm}) \rightarrow p + e$
2. Recombination
   $p + e \rightarrow \mathrm{H}^* + h\nu$
3. Cascading
   $\mathrm{H}^* \rightarrow \mathrm{H} + h\nu$
4. Collisional excitation
   $\mathrm{O}^{++} + e \rightarrow (\mathrm{O}^{++})^* + e$
5. Radiative de-excitation
   $(\mathrm{O}^{++})^* \rightarrow \mathrm{O}^{++} + h\nu$

The brightest emission lines originate either as recombination spectrum when ionized atoms recombine and electrons cascade to lower levels, or when collisionally excited atoms with lifetimes lower compared to the collisional times in the gas, de-excite radiatively. The latter transitions are either magnetic dipole or electrical quadrupole in nature and hence are "forbidden" at higher densities in the laboratory. If the ionization is in equilibrium with recombination, the recombination lines provide us information on the luminosity of ionizing photons and hence the nature of ionizing source. Their fluxes can be used to infer total mass of ionized gas. Ratios of recombination lines of different ionic species can be used to estimate the relative abundances of these species using the atomic parameters such as recombination cross-section and transition probabilities known from theory and laboratory experiments. Hydrogen Balmer line ratios are also used for estimating the amount of extinction by the foreground dust.

Collisional excitation rates depend on electron density and temperature, apart from the collision cross-sections determined theoretically and in laboratory. The forbidden lines can be used to estimate these physical conditions in the gas better than recombination lines due to their increased sensitivity. They can also be used to estimate the relative abundances of the species producing them.

The physical conditions in the gas are determined by computing the level populations with N relevant levels included in the calculations, and are hence termed N-level atom. The results include emission line fluxes over the entire electromagnetic spectrum, and also continuum due to free-free, free-bound and two-photon transitions in the case of recombination spectrum. The complications include radiative transfer of ionizing radiation as well as of the emitted spectrum, especially the ground-state recombination radiation since it can also provide ionizing photons. The clumpiness of gas and its geometric distribution are also additional factors. Osterbrock & Ferland (2005) provide many results on simple cases with references and describe complexities. Ferland et al. (1998) have made a software available for numerical modeling of spectra of astrophysical plasmas in a general situation where complexities can easily be added. The software is continuously upgraded with inclusion of more accurate atomic parameters as they become available. The current version of the software is called CLOUDY90 (http://www.nublado.org). There are third party graphic user interfaces and add-ons available over the web.

3 Sites of emission lines

Emission lines are emitted by ionized or excited gas and become visible when no strong continuum source is behind the gas. Gas is present in the universe at all densities ranging from the most diffuse intergalactic matter to the high densities in stellar atmospheres. It can get photoionized by stellar radiation above the ionization limit of the species, and also by shocks. Energetic particles may also contribute to ionization. Gas can similarly be excited by photoabsorption, or by collision with particles, especially free electrons. Emission lines are produced by radiative recombination and radiative de-excitation of atoms and molecules. We list below some examples of objects that exhibit emission lines in their spectra. Examples are provided based on optical observations obtained with the Himalayan Faint Object Spectrograph (HFOSC) on the 2-m Himalayan Chandra Telescope (HCT) at Indian Astronomical Observatory (IAO), Hanle.

Sun and Sun-like stars: The nearest example of an astrophysical site of emission lines is the Sun. The emission lines arise in the outermost layers of solar atmosphere: permitted lines of hydrogen balmer lines and resonance lines of heavier elements arise in the chromosphere, and forbidden lines of highly ionized elements such as Fe^{+9} and Fe^{+14} occur in an extended corona. The high ionization is due to collisional processes, and details are under debate. Though the solar corona is intrinsically much fainter than the photosphere, it can be observed when the photosphere is eclipsed by moon, or by artificially masking it in coronagraphs in space or high altitude sites. Chromosphere and coronae are spectroscopically inferred in other stars when they exhibit solar-type activity at much higher intensity.

Pre-main sequence stars: Just-born stars have a lot of gas around them, some of which is continually accreted by the stars. The gas falling into the central gravitational potential well gets heated and exhibits emission line spectrum. Variations in the accretion rates as also instabilities in the accretion disc that forms around the star due to the angular momentum of gas, result in variability in the total emitted radiation as well as in the individual emission lines. Hotter stars ionize the gas around them and provide a different phenomenology described as H II regions.

Be and shell stars: Young stars may rotate fast due to the angular momentum of the gas from which they formed. Their atmosphere would hence

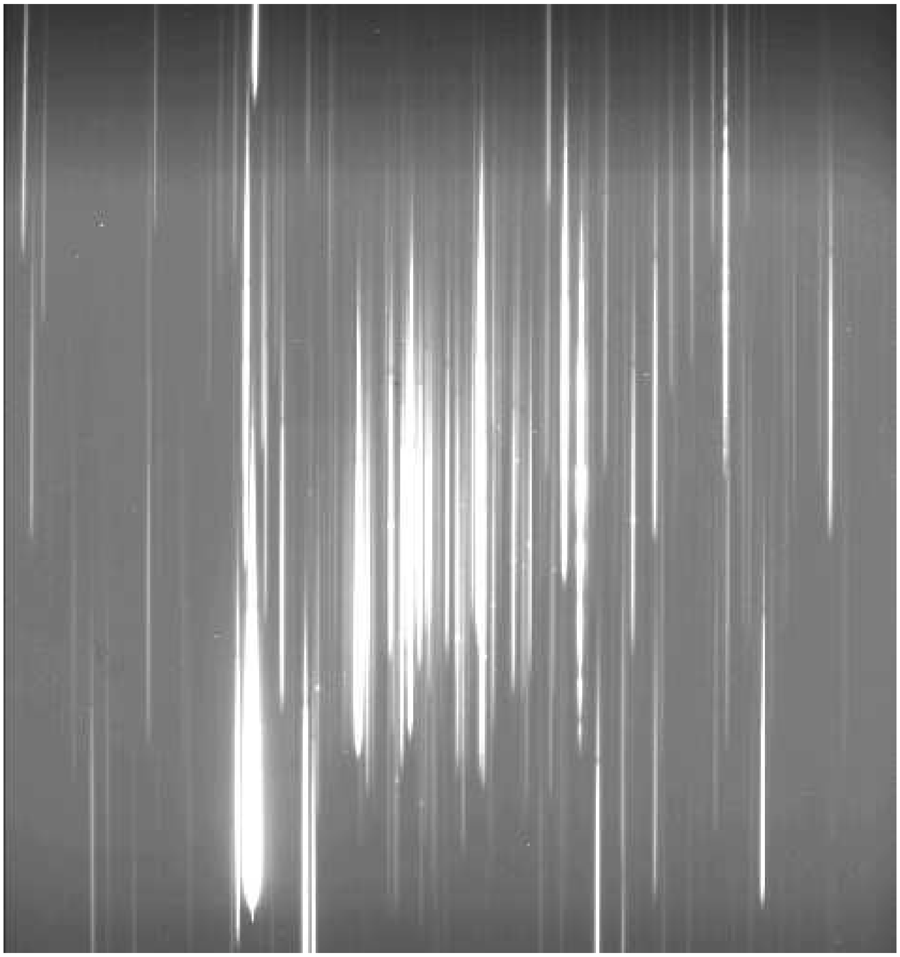

Fig. 1. Slitless pectra of stars in the open star cluster NGC 7419 obtained with the HFOSC instrument on 2-m HCT (Subramaniam et al. 2006). The emission line stars show the emission line of Balmer Hα superposed as a bright dot over the continuous spectrum seen as a bright line.

be extended and some gas may be continously lost to the circumstellar regions. In the case of hot stars of B or early A spectral types, the gas in the extended atmosphere as well as circumstellar region is ionized by the radiation from stellar photosphere and produces recombination spectrum. Such stars are easily recognized by rotationally broadened emission lines, especially Hα (cf. Figure 1). The emission line objects discovered through such surveys are studied in greater detail with slit spectroscopy at higher resolution. Occasionally a shell or ring of gas is detached from the stellar surface, which is called a shell phase. The emission lines show a central absorption due to gas between the photosphere and observer, which may be slightly blueshifted when material is being ejected from the photosphere.

H II regions: The black-body radiation from young, massive stars, as also evolved massive stars that have shed their outer envelope ('Wolf-Rayet stars') peaks in the ultraviolet which photo-ionizes the left-over gas surrounding the star. The ionized region around such stars is referred to as H II region following spectroscopic terminology. The region is rich in emission lines due to recombination of hydrogen, and also a variety of permitted and forbidden lines of heavier elements. The densities in the gas being low, such regions were the first to be modeled theoretically and have provided an abundance of information on the physical conditions in the gas not only in our galaxy, but in galaxies showing current star formation over the entire universe. Figure 2 shows a spectrum of extragalactic star-forming region obtained with HCT.

Evolved stars: Emission lines are observed from a variety of stars that evolve into supergiants when their atmosphere becomes highly extended. Stars that expand into giants and supergiants in the course of evolution lose matter in steady winds. The emission from expanding or rotating atmospheres can be distinguished through their line profiles: expanding atmospheres show blue-shifted absorption due to gas in front of the photosphere which is approaching the observer (named after the prototype star P Cygni); rotating atmospheres show double-peaked profiles with unshifted absorption.

End states of stellar evolution: Most stars end their life as a compact core left after nuclear burning. The outer envelope of the star is ejected when the compact core collapses and would often glow due to radiation from the compact object apart from possible shocks in the gas.

In the case of stars in the mass range of 1-8 $M_\odot$ the electron degeneracy sets in leaving a white dwarf in the core. The outer envelope is ejected into a shell which is called a Planetary Nebula for historical reasons: the nebula looked like a planetary disk in small telescopes. The white dwarf is hot, with an effective temperature of about 100,000 K. The black-body radiation from the hot white dwarf ionizes the shell. Though the densities are somewhat higher compared to H II regions, and the ionizing source hotter, the physical conditions in the shell can be studied in a manner similar to H II regions.

In the case of stars more massive than 8 $M_\odot$ the gravitational pressure of outer layers is high and the core collapses to a neutron star (up to about 30 $M_\odot$) or a black hole ($> 30M_\odot$). The mass of the core is comparable to Sun and hence a large quantity of matter in the envelope is ejected in Supernova explosions. Some gas is ejected also in the pre-supernova phase as slow winds. The supernova stage permits real-time probing of different layers of the exploding star and the circumstellar matter adds other interesting phenomenology to the problem. Figures 3 and 4 show the evolution of the spectrum of supernova SN2006jc. The progenitor of this supernova is estimated to be around 40 $M_\odot$ which had undergone extensive mass loss during the earlier evolutionary phase, turning it into a hot Wolf-Rayet star of about 7

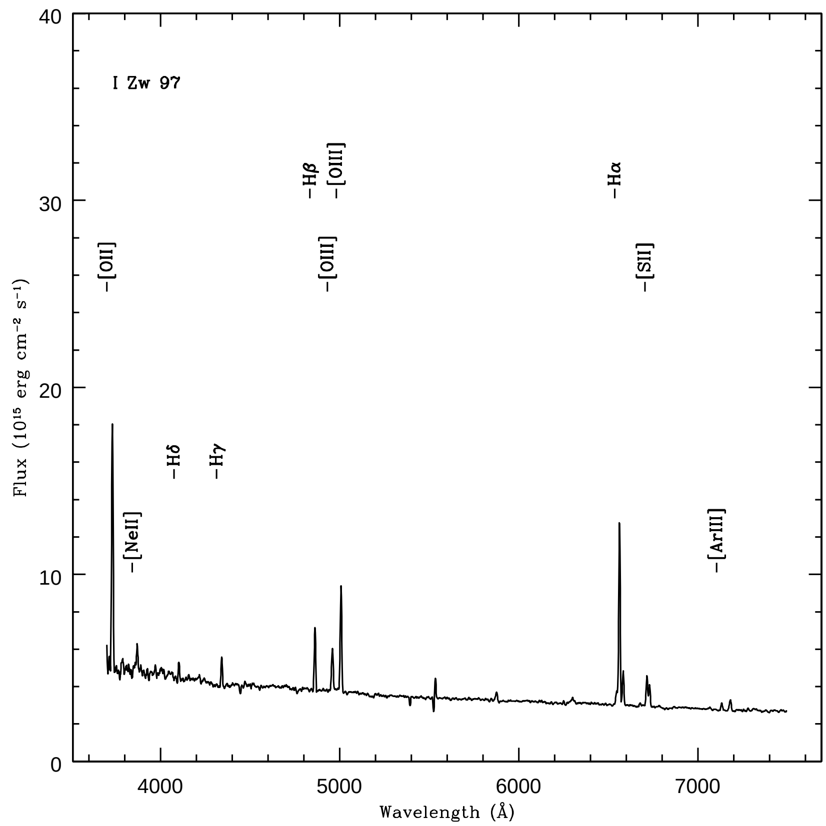

Fig. 2. Spectrum of a star-forming region in a Blue Compact Dwarf galaxy I Zw 97 obtained with the HFOSC instrument on 2-m HCT (Ramya Sahu & Prabhu 2009). The permitted emission lines of hydrogen Balmer series, and forbidden lines of O, Ne, S and Ar are seen above the continuum radiation from the underlying stars. The absorption and emission at 557.7 nm is due to the airglow in earth's atmosphere which is partially subtracted.

$M_\odot$ before the explosion. The He emission lines arise in He-rich circumstellar matter ejected earlier (Anupama et al. 2009).

Interacting binary stars: Close binary stars distort the gravitational field around them permitting mass transfer from inner Lagrangian point from a star that fills the potential up to this size ('Roche Lobe'). Part of the transferred gas settles into an accretion disk around the companion star and a part is ejected away from the system carrying energy and angular momentum with it. The accretion disk loses angular momentum due to viscous forces that heat it and matter falls onto the companion from the inner regions of the accretion

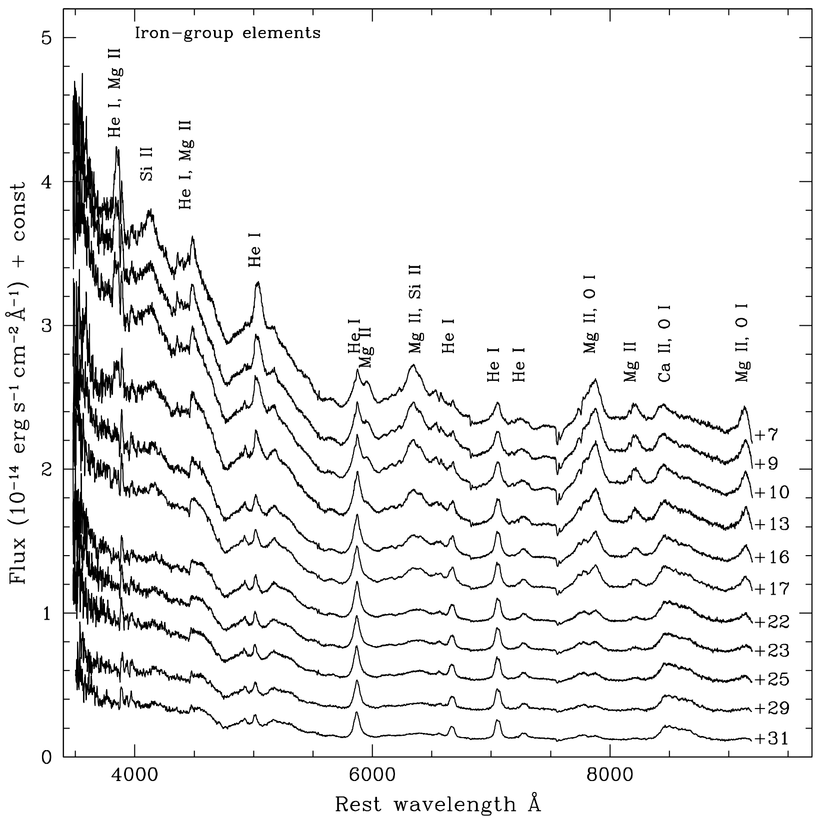

Fig. 3. Spectral evolution of the core-collapse supernova SN2006jc over the first month since the outburst (Anupama et al. 2009). Broad emission lines due to Ca, Mg and Si are seen. Intermediate width He emission lines arise in the circumstellar material ejected from the star during the period before the supernova explosion. They provide information on the amount of matter ejected and physical conditions therein. Spectra were recorded with HFOSC on 2-m HCT.

disk. This environment provides interesting phenomenology due to excited gas in different regions between and around the binary system.

A class of interacting binary systems may have a compact star as a primary resulting from the faster evolution of the progenitor star. If the compact star is a white dwarf, the binary is called a cataclysmic binary since sudden brightening is noticed in such objects often due to instabilities in the accretion disk ('dwarf nova'), and occasionally due to explosions resulting from run-away thermonuclear processes in the mass accreted by the white dwarf. While a part of the accreted matter is ejected in this process, a part is retained

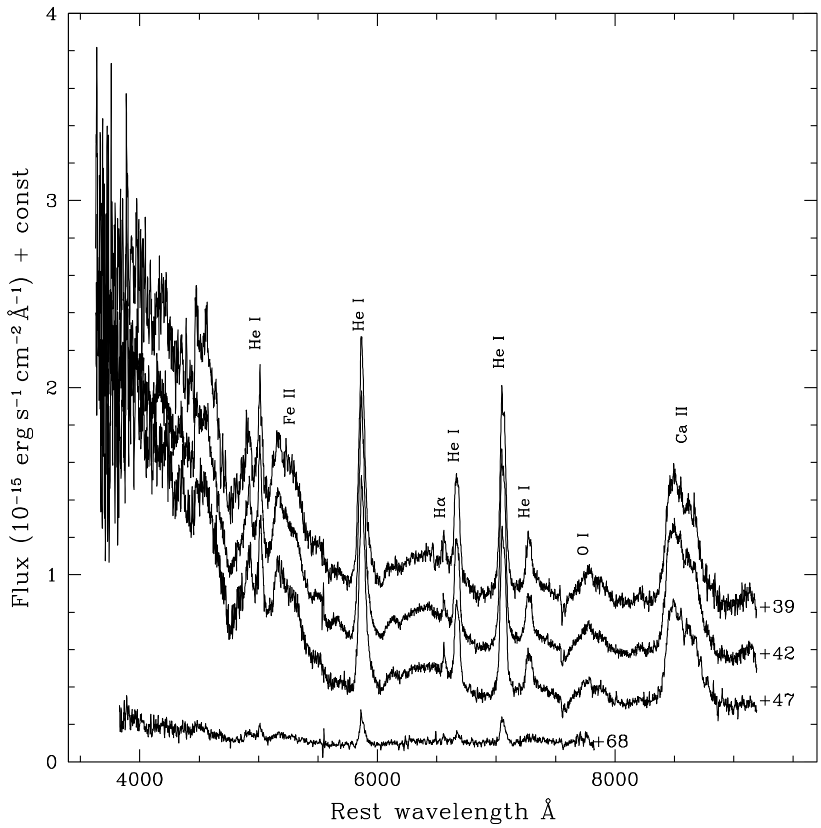

Fig. 4. Spectral evolution of the core-collapse supernova SN2006jc over the second month since the outburst (Anupama et al. 2009). Note the increased brightness of He I lines and appearance of Hα and O I lines. Lines due to Ca and Fe are also present. Spectra were recorded with HFOSC on 2-m HCT.

making the white dwarf grow in mass. The white dwarf has to collapse again if it reaches the limit of Chandrasekhar mass, resulting in another class of supernovae (Type Ia). Similar explosions resulting from detonation or deflagration can occur also when two white dwarfs forming a binary system spiral in and coalesce leading to growth above Chandrasekhar limit.

Low-mass X-ray binaries (LMXB) have a neutron star primary and High-mass X-ray binaries (HMXB) have a black hole primary. These objects also have ionized and excited gas in the accretion disk and circumbinary region.

External galaxies: While it is possible to study objects similar to the ones described above in nearby galaxies, external galaxies can be studied generally only at a poorer spatial resolution with smaller ground-based telescopes.

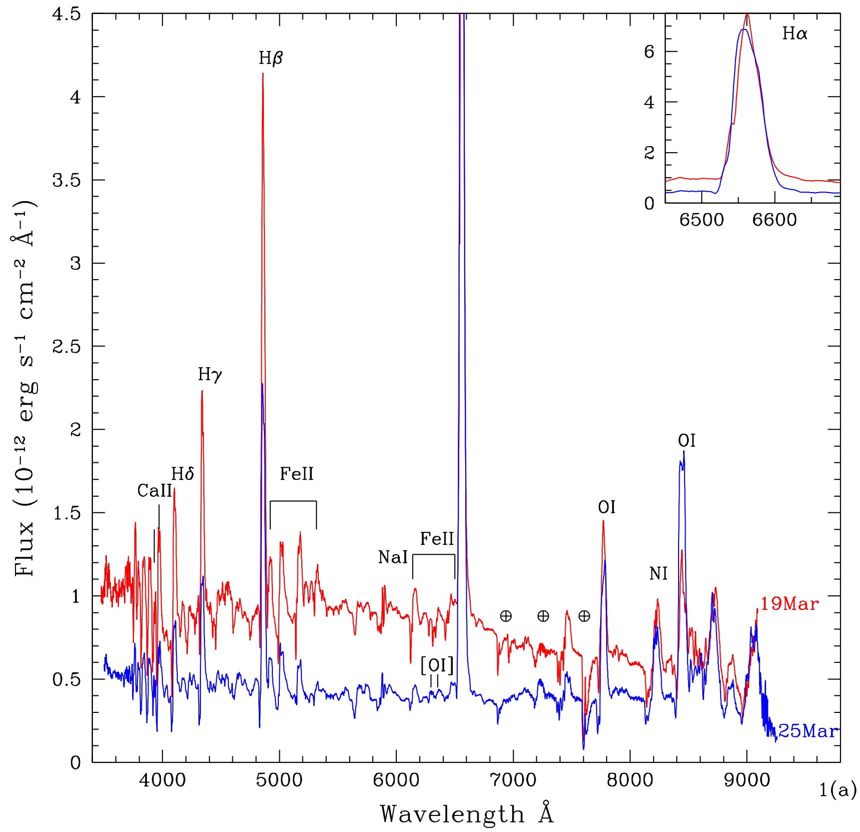

Fig. 5. Spectral evolution of Nova V5114 Sgr over the first month since its explosion (G. C. Anupama personal communication). Spectra were recorded with HFOSC on 2-m HCT.

The emission lines from neutral and ionized hydrogen is often used to obtain information on the kinematics of galaxies. Galaxy rotation curves have proved the existence of unseen, 'dark matter' in them. The star forming complexes in galaxies can be studied in a manner similar to H II regions in our Galaxy, to infer the physical conditions including star formation rates and abundances of light elements. Light from farther (high redshift) galaxies takes a long time to reach us,and a study of star formation rates at different redshifts helps us to infer galaxy formation and evolution on cosmological timescales.

Active nuclei of galaxies are of considerable astrophysical interest. It is well-accepted now after a great deal of hesitation that they contain super-massive ($> 10^6 M_\odot$) black holes with accretion and ejection phenomena at various scales ranging from parsec to megaparsec. Active galactic nuclei are

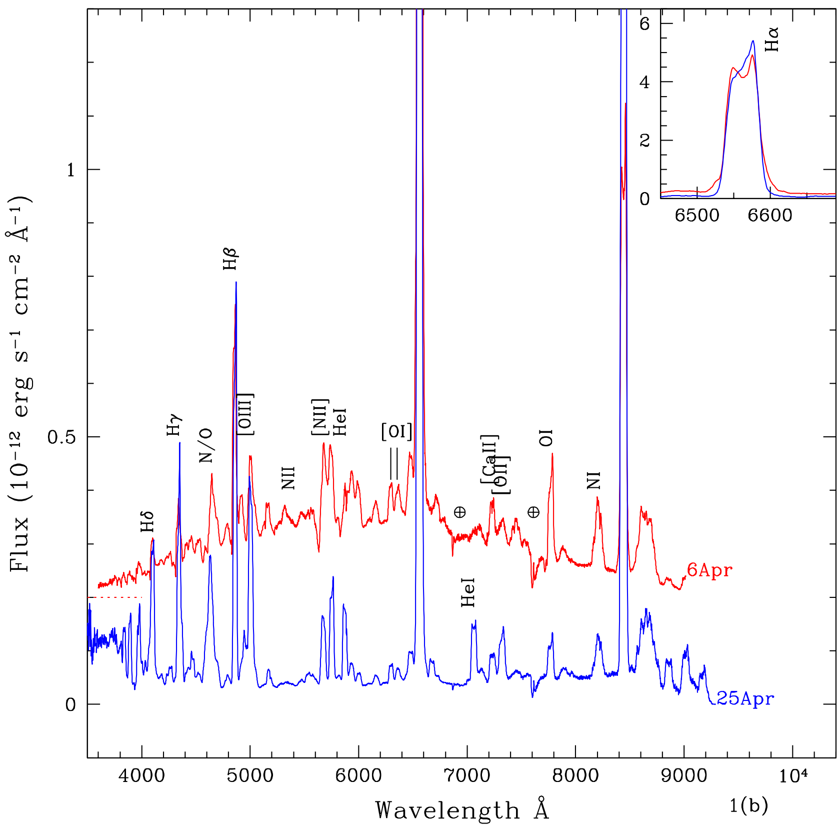

Fig. 6. Spectral evolution of Nova V5114 Sgr a few months after its explosion (G. C. Anupama, personal communication). Spectra were recorded with HFOSC on 2-m HCT.

classified into different types based on spectroscopic information, and relative importance of different phenomena which appears to be largely determined by the mass of the black hole, accretion rate, immediate environment, and viewing angle.

4 Conclusion

It is shown in this brief review that emission lines arise from a variety of astrophysical phenomena, and provide important information on the physical conditions in these sites that includes the electron temperatures and densities, total emitting mass, and foreground reddening. This information and

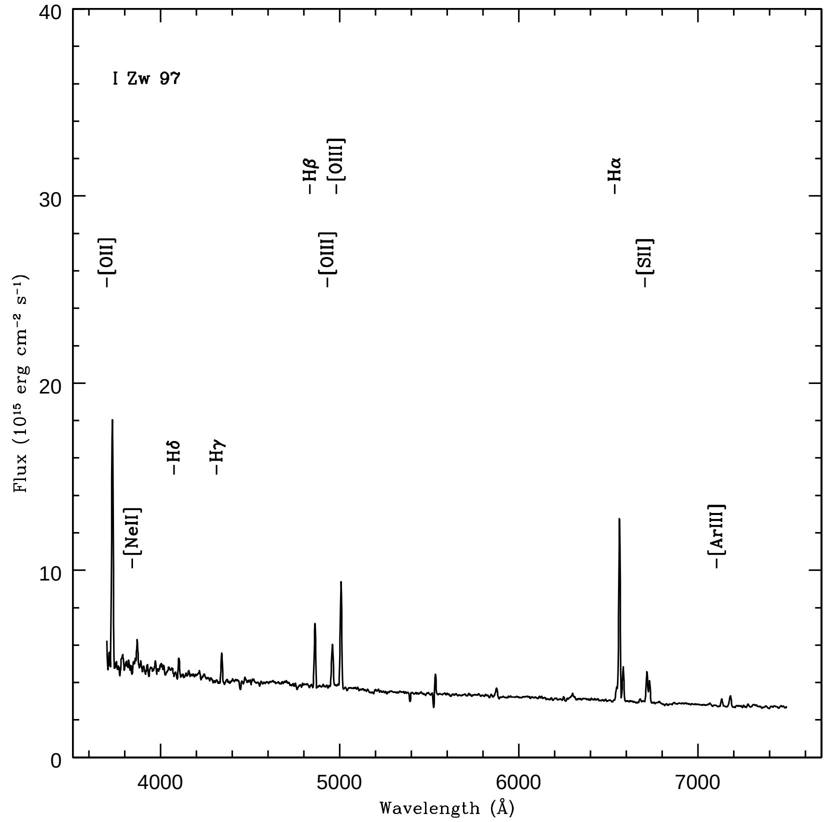

Fig. 7. Spectrum of nucleus of the Blue Compact Dwarf galaxy Mkn 104 obtained with the HFOSC instrument on 2-m HCT (Ramya Sahu & Prabhu 2009). The permitted emission lines of hydrogen Balmer series, and forbidden lines of O, Ne, S and Ar are seen above the continuum due to underlying stars. The absorption and emission at 557.7 nm is due to the airglow in earth's atmosphere which is partially subtracted.

the velocity structure derived from line profiles helps in modeling the entire line-emitting region.

The information can be derived often from simple numerical models and at times with the inclusion of some complexities. The readers are referred to the excellent text book of Osterbrock & Ferland 2005 and the manual of software CLOUDY which can be downloaded from the website http://www.nublado.org/.

I would like to emphasize here the importance of theoretical atomic data and its verification in the laboratory which forms an input to the numerical models and controls the accuracy of inferences.

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