AGNAGN Seminar Sec12-12.3

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12.1 Introduction

- novae & supernovae: shells of gas are cast off from evolving star and returned to interstellar space
  - much more violent than planetary nebulae
    - velocity of expansion
      - nova shells: $\sim 10^3$ km/s
      - supernova shells: $\sim 10^{3-4}$ km/s
  - mass of nova shells are much smaller than planetary-nebula shells
    - planetary-nebula shells: $\lesssim 10^{-4} M_{\odot}$
    - supernova shells: $\gtrsim 1 M_{\odot}$
  - observed line spectra have general similarities
    - heated and ionized gas tends to radiate more or less the same emission-line photons, regardless of the mechanisms

→discuss each shells

12.2 Nova Shells

- novae: evolving star suddenly becomes much brighter, reaching $L \gtrsim 10^4 L_\odot$
  - spectra→material leaves the star with $v \sim 10^3$ km/s
  - emission-line profiles→indicate multiple "shells"
  - release $E > 10^{45}$ erg/year, and gradually return to pre-outburst state ($\approx 10^2$ yr)
- physical mechanism of novae
  - close binary stars (white dwarf & red dwarf or subgiant)

  →overflow subgiant's Roche lobe and lose mass into white dwarf's lobe

  →inflowing mass spirals into white dwarf as an accretion disk

  →build-up of hydrogen-rich material on the surface of the white dwarf

  →the temperature at its inner edge rises

  →start explosive thermonuclear runaway

  →energizes the nova outburst

Figure 12.1
The shells around the novae DQ Her (left) and GK Per. DQ Her erupted in 1934 and its shell had a diameter of roughly 20″ when this image was taken. GK Per erupted in 1901. (GK Per, WIYN Observatory)

  - ejecta: mixture of gas with a composition from the subgiant and material from the white dwarf
  - nova explosions repeat every $\sim 10^4 - 10^5$ yr

Spectrum

- initial stage
  - dense and optically thick from UV to infrared
  - form a photosphere similar to A-F supergiant with broad blue-shifted absorption lines
- soon after the peak luminosity
  - the density of the shell falls, the gas becomes optically thin
  - begins to show emission lines of HI and HeI
- as the continuum weakens
  - the emission lines strengthen
  - typical nebular lines ([NII], [OIII], [NeIII]) start to appear and become stronger
    - initially, the density is above the critical of the nebular lines
      - they are faint
      - [NII]λ5755 and [OIII]λ4363 are relatively strong due to the high density
    - as the density falls below the critical densities
      - [NII]λ5755 and [OIII]λ4363 weaken with respect to [NII]$\lambda\lambda$6548, 6583 and [OIII]$\lambda\lambda$4959, 5007
- spectrum gradually changes to an almost pure nebular-type spectrum
  - broad emission lines resulting from the high expansion velocity

Growth of nova shell

・a few years after the outburst

・the ejecta becomes a small, faint nebulous shell surrounding the post-nova star

→expand at constant-velocity

→gradually become fainter

→eventually merge into and become part of ISM

・distance of a nova shell

・determined by comparing the measured radial velocity of expansion with the proper motion (or angular velocity) of expansion

・DQ Her (Nova Herculis 1934)

・measured radial expansion velocity: 320±20 km/s

・the dimensions of the shell: 11” x 17”

→ distance: 420±100 pc

・uncertainty: the major or minor axis of the elliptical shell

Spectra of shell

- nova shells have quite unusual nebular spectra
  - many permitted lines of various stages of ionization of N and C
  - normal HI, HeI and HeII lines
  - a very few forbidden lines ([NII]$\lambda\lambda$6548, 6583 and [OII]λ3121)
- reason of the nearly complete absence of forbidden lines from these optical spectra
  - the temperature is so low that they all are suppressed
    - thresholds for excitation χ is much larger than thermal energies ($\exp(-\chi/kT) \ll 1$)
    - at low temperatures, only recombination lines are expected to be visible in the spectra of nebula
      - for a collisionally excited line near 6000Å, T < 3,500 K is required for $\exp(-\chi/kT) < 10^{-3}$
      - the strongest expected lines in the optical spectrum are Hα Hβ, HeIλ5876, and HeIIλ4686 for HI and He
        - observed in nova shells

abundance of the elements in nova shells

・relative abundances of the elements in nova shells can be determined from the relative strengths of their emission lines

・CII ($2s^2 2p\ ^2p^o - 2s2p\ ^2D\ \lambda 1335$): strong because of dielectronic recombination of C^{++} through C^+

・observational data→nova shells are somewhat enriched in He, and greatly enriched in C, N, & O, compared to unevolved stars

⇨significantly contribute to the present abundances of heavy elements in ISM

・large abundances of C, N, and O

→explain the low temperature and the near absence of forbidden lines in the observed spectrum

・even at low temperatures, the rate of collisionally excited far-infrared line radiation is very large

⇨equilibrium temperature is quite small by higher radiative cooling rates

Model of a nova shell

・photoionization model of a nova shell can be calculated by similar ways of HII regions and planetary nebulae

・In a nova, the source of the ionizing radiation is the accretion disk around the white dwarf

・the shell is not a simple sphere and the spectra of the minor and major axes are different

1. genuine composition or density differences
2. the more distant portions of the shell receive a lower flux
3. the shape of the ionizing continuum may be different

・ best models (Table 12.1) make distinctions between the major and minor axes

→reproduces qualitatively all its main features

・quite different from the ordinary HII regions and planetary nebulae

・the high-energy photon processes is taken into account to calculation

・main source of excitation of [OII]λ3727

・photoionization of O^0 by photons

↔ collisional excitation of O^+ in typical HII regions and planetary nebulae

・main cooling source in nova shells: collisional excitation and line radiation from N^+, N^{++}, and O^{++}

・observation of these emission lines provide a direct measure of the major coolants

12.3 The Crab Nebula

- supernovae: much higher luminosities than novae ($M_{bol} \approx \sim -18 - -20,\ L \approx 10^9 - 10^{10} L_\odot$)
  - Type II: show hydrogen emission lines
    - imply the presence of hydrogen in the outer envelope of the evolved star
    - end stages in the evolution of massive stars ($M \gtrsim 8 M_\odot$)
      - H burning, He burning, and further thermonuclear burning stages lead to heavy nuclei

      →central core collapses to a neutron star or black hole, and a shell is expelled with high velocity
    - eject greater masses ($\sim 10 M_\odot$) and lower luminosities ($M_{bol} \approx -18$)

Classification of supernovae

- Type I: don’t show hydrogen emission lines
  →suggest that they originate from a source with little hydrogen
  - Type Ia: show Si lines
    - resulting from the thermonuclear destruction of white dwarf
      - accrete white dwarfs in binary systems
        →grow to exceed the Chandrasekhar limit
        →ignite a C (or He) detonation
    - progenitors or outputs are a homogeneous group
      →used as standard candles to large distances
    - Type Ia eject lower masses ($\sim 1 M_{\odot}$) and higher luminosities ($M_{bol} \approx -19.6$)
  - Type Ib: don’t show Si lines, but have He lines
  - Type Ic: don’t show Si nor He lines
    - Type Ib and Ic: massive stars which have lost their hydrogen-rich outer envelop by stellar winds or the explosion that is similar to Type II

Crab Nebula

- Crab Nebula (NGC 1952): the remnant of a supernova
  - show hydrogen emission lines with a relatively strong
    →Type II supernova
    - the emission lines are concentrated in the filaments (Figure 12.2a)
    - the continuum arises in the amorphous gas (Figure 12.2b)
  - the radial velocity splitting at the center: ~2900 km/s
    →expansion velocity: 1450 km/s
      - much larger than in planetaries but considerably less than typical supernova
  - a pulsar very near the center of the Crab Nebula
    →the neutron star remnant of the original pre-supernova star
  - an extremely strong radio source
    - emission mechanism that produces both the radio-frequency and amorphous optical continuum
      - synchrotron emission

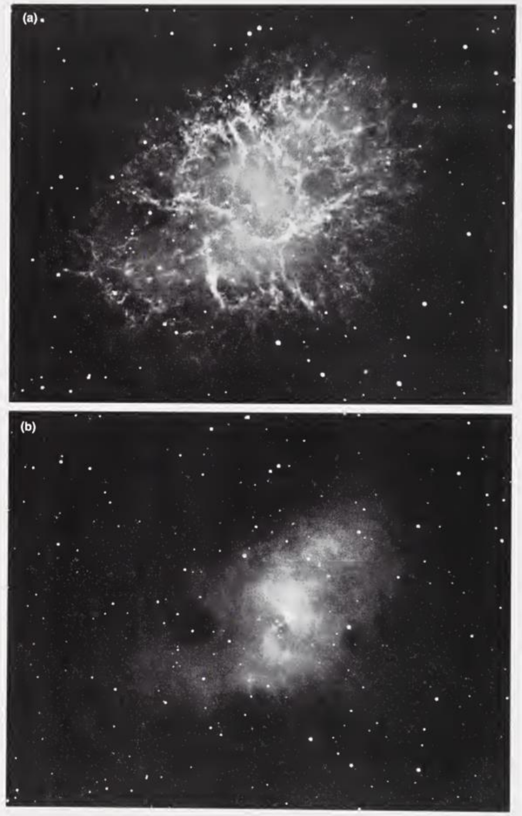

Figure 12.2
NGC 1952 (Crab Nebula). Both photos were taken with the Shane 3-m reflector. The upper photo (a) was taken with a red filter-plate combination transmitting chiefly Hα, [N II]. The lower photo (b) was taken with a yellow filter-plate combination transmitting chiefly continuum radiation. (©UC Regents/Lick Observatory)

emission-line spectrum of the Crab Nebula

・typical nebular lines (HI, HeI, HeII, [OII], [OIII], [NII], etc.)
・a wide range of ionization, including relatively strong [OI], [SII], and [NeV]

・[OII]$\lambda\lambda$3726, 3729 and [SII]$\lambda\lambda$6716, 6731 line ratios
→typical electron densities $n_e \approx 10^3\ \mathrm{cm}^{-3}$
・[OIII](λ4959+λ5007)/λ4363 → mean temperature T = 15,000 K
　・the corresponding ratio for [NII] → T = 7,400 K
・derived average abundances over the entire nebula
　・$[n(He^+) + n(He^{++})]/n(H^+) = 0.47$
　・$[n(O^+) + n(O^{++})]/n(H^+) = 10^{-3.5}$
　・$n(N^+)/n(H^+) = 10^{-4.0}$
⇨・the material in the filaments is He-rich (result of nuclear processing)
　・abundances of N and O compared to H are approximately normal
　　・low compared to H + He

Structure of Crab Nebula filaments

・derived temperatures and abundances
⇨photoionization is the main mechanism to the ionized gas in the filaments
・the continuum of the amorphous region of NGC 1952 through the optical into the near UV
→can be fit with the X-ray flux from the Crab Nebula
・optical continuum is strongly polarized
・luminosity and polarization fit smoothly to the radio-frequency region
・optical continuum of the amorphous region of NGC 1952 is due to synchrotron emission
・the radio continuum, and the UV and X-ray continua, too

・magnetic field of the rotating neutron star gives energy to the gas near it
・part of energy goes into expanding the nebula
・the rest into accelerating electrons that produce the synchrotron radiation
⇨filaments: regarded as high-density regions photoionized by source of continuum radiation
・direct photographs→synchrotron source is extended
・kinematic studies→filaments are in a thick shell surrounding the extended source

Model of Crab Nebula filaments

- the observed and calculated line spectra agree qualitatively (Table 12.4)
  - models reproduce the observed great strengths of [OI]λ6300, 6364 and [SII]$\lambda\lambda$6716, 6731
    - result of the relatively large fraction of high-energy photons in the photoionizing spectrum
      - high-energy photons have a small absorption cross section

        →a significantly larger "transition legion" than HII regions

        →in this transition region, H^0, O^0, H^+, S^+, and electrons can all coexist

        →collisionally excited [OI] and [SII] lines are emitted
- the calculated Hα/Hβ is significantly larger than the recombination value (2.85)
  - collisional excitation of Hα from its ground level in this same transition zone
- estimate total mass of the gas in the filament from luminosity and mean density

  →$\sim 1.5 M_\odot$
    - may be larger if there are significant amounts of nearly neutral gas protected from ionizing radiation