AGNAGN Seminar
Sec7.3-7.5

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7.3 Dust within HII Regions

globules

・dust is present within HII regions

→ **“absorption”** features in nebula

・cut down the nebular emission and starlight from beyond the nebula

・**globules**: very dense small features

・elephant-trunk or comet-tail structures: other absorption features at the edges of nebulae

・appear to be almost completely dark

⇨have a large optical depth at the observed wavelength and are on the near side of the nebula

・it’s difficult to study absorption features quantitatively

↔can estimate their optical depths

→the amount of dust can be estimated if its optical properties are known

・if the gas-to-dust ratio is known, the total mass in the structure can be estimated

Observation of continuum

・**dust particles scatter the continuous radiation of the stars in nebulae**

→observable nebular continuum

・must be made with sufficient spectral resolution or filters to avoid the strong nebular lines

・measurements of an HI recombination line are made at the same time

・the expected nebular atomic continuum caused by bound-free and free-free emission can be calculated from the intensity (Section 4.3)

→**dust-scattered continuum** = **observed continuum － atomic contribution**

・dust-scattered continuum is considerably larger than the atomic continuum in most nebulae

↔observational data can't be interpreted in a straightforward and unique way

・due to the complexity of geometry and spatial structure of nebulae

・amount of scattered light depends strongly upon these factors

Principle of observational data

- principles involved with observation
  - treat the simplified problem of a spherical, homogeneous nebula illuminated by a single central star
  - suppose that the nebula is optically thin

→ • flux of starlight within the nebula: $\pi F_\nu = \frac{L_\nu}{4\pi r^2}$.

- L_ν: luminosity of the star per unit frequency interval
- r: distance from the star

→emission coefficient per unit volume per unit solid angle due to scattering: $j_\nu = \frac{a_\lambda n_D C_\lambda \pi F_\nu}{4\pi} = \frac{a_\lambda n_D C_\lambda L_\nu}{16\pi^2 r^2}$,

- $n_D C_\lambda$: extinction cross section per unit volume
  - n_D: number of dust particles per unit volume in the nebula
  - C_λ : average extinction cross section at the wavelength λ
- a_λ: albedo, fraction of the radiation removed from the flux that is scattered
  - $1 - a_\lambda$: fraction that is absorbed
- the scattering has been assumed to be spherically symmetric

→intensity of the scattered continuum radiation:

$$I_\nu(b) = \int j_\nu \, ds = \frac{a_\lambda n_D C_\lambda L_\nu}{8\pi^2} \cdot \frac{1}{b} \cos^{-1} \frac{b}{r_0}$$

- r_0: radius of nebula
- b: minimum distance from the central star in a nebula

Comparison with Hβ

・**compare with the Hβ surface brightness** observed from the same nebula

・intensity at Hβ: $I_{\mathrm{H}\beta}(b) = \int j_{\mathrm{H}\beta} ds = \frac{1}{4\pi} n_p n_e \alpha^{eff}_{\mathrm{H}\beta} h\nu_{\mathrm{H}\beta} 2\sqrt{r_1^2 - b^2}$ (r_l: Stromgren radius)

→ratio of surface brightness in Hβ to surface brightness:

$$\frac{I_{\mathrm{H}\beta}(b)}{I_\nu(b)} = \left[\frac{n_p n_e \alpha^{eff}_{\mathrm{H}\beta} h\nu_{\mathrm{H}\beta}}{a_\lambda n_D C_\lambda}\right]\left(\frac{4\pi D^2}{L_\nu}\right)\left(\frac{r_0 r_1}{D^2}\right)\left[\frac{\left(b/r_0\right)\sqrt{1-\left(b/r_0\right)^2}}{\cos^{-1}\left(b/r_0\right)}\right]$$

- involves atomic properties and dust properties
- 1/(observed flux from the star)
- r_0/D (angular radii of the nebula in the continuum) × r_l/D (in Hβ)
- angular dependence of the surface brightnesses in dimensionless ratios

・D: distance between the nebula and the observer

→first factor can be determined from measurements of surface brightnesses and of the flux from the star

・when the electron density is determined either from the Hβ surface brightness measurements or from [OIII] or [SII] line-ratio measurements

→ $n_p/a_\lambda n_D C_\lambda$ (proportional to the ratio of densities of gas to dust) is determined

Scattering of emission line & estimate of amount of the dust

- **the emission-line radiation emitted by the gas is also be scattered**
  - if $a_\lambda = 1$ at all wavelengths, scattering don't affect the total emission-line flux from the whole nebula
    - every photon generated in the nebula escape
  - ⇔ in reality, $a_\lambda < 1$
    - some emission-line photons are destroyed by dust within the nebula
    - ⇨accurately, the procedure for correcting observed nebular emission line intensities for interstellar extinction (Section7.2) is not correct
      - it's based on stellar measurements, in which radiation scattered by dust doesn't reach the observer
      - ⇔numerical calculations of model nebulae show that this corrections are approximately correct
- estimate the amount of dust within a globule with radius 0.05pc
  - optical depth along its diameter: $\tau_{H\beta} \geq 4$ (appear quite opaque)
  - suppose that the dust in the globule has the same properties as the dust in the ionized region of the nebula
  - → $n_D \geq 2 \times 10^{-8}\ \mathrm{cm}^{-3}$ (dust)
  - suppose that the gas-to-dust ratio is the same
  - → $n_H \geq 2 \times 10^{4}\ \mathrm{cm}^{-3}$ (gas)
  - ⇨indicates **quite high gas densities in this type of globule**

7.4 Infrared Thermal Emission

- **Dust is also observed in HII regions** by its infrared thermal emission
  - high-resolution measurements have shown spectral features in the infrared radiation from dust
    - the infrared radiation in HII regions is far greater than the free-free and bound-free continuous radiation predicted from the observed Hβ and radio-frequency intensities
- the observational data of NGC 1976
  - several infrared “point” sources
    - at least one of which (the “Becklin-Neugebauer (BN) object”) is a highly luminous, heavily reddened star
      - in the dense molecular cloud, and behind the ionized nebula
  - two extended peaks of intensity are measured at 10um and 20um
    - one centered approximately on the Trapezium (Ney-Allen nebula)
    - the other centered approximately on the BN object on the northwest of the Trapezium (Kleinmann-Low nebula)
  - At much longer wavelengths (100um, 350um)
    - the Kleinmann-Low nebula remains a bright feature
    - the Ney-Allen nebula can’t be distinguished from the background

observational data of nebula (NGC1976)

- measured large nebular infrared continuous radiation can only explained by radiation from dust
  - as a approximation, the dust emits a dilute blackbody spectrum

    ⇨**measurements at two wavelengths approximately determine its temperature**
    - Ney-Allen nebula
      - the “color temperature” determined from the measured fluxes at 11.6um and 20um in this way: $T_C \approx 220K$
        - approximately represent the temperature of dust particles
        - heated to this temperature by the absorption of UV and optical radiation from the Trapezium stars
          - radiation from the nearby nebular gas that is ionized by samse stars may also contribute
    - Kleinmann-Low nebula
      - observed dust is heated by absorption of shorter wavelength radiation emitted by the BN star within it

    ⇨NGC 1976 is an ionized region at the edge of a giant dust cloud
    - Kleinmann-Low nebula is a dense region within the cloud but near its ionized surface
- a relatively sharp peak at 9.8um, similar to the sharp peak observed in the infrared emission of many cool stars
  - FWHM: 2.5um
  - attributed to silicate particles, which have a band near this position

Narrow features in HII region

・**narrower infrared features are also observed in HII regions, and several planetary nebulae**

・too broad to be emission lines of ions

⇨probably the result of infrared fluorescence from vibrationally excited PAH molecules, or hydrogenated amorphous carbon particles

→large molecules or small particles are excited by UV and optical radiation

→decay to excited vibrational levels which emit photons in the 3.28um and other bands

→decay to the ground level

・this emission is due to the temperature spike (“**quantum heating**”)

・immediately heating by absorption of the photon, and the subsequent cooling that continues until the arrival of the next photon

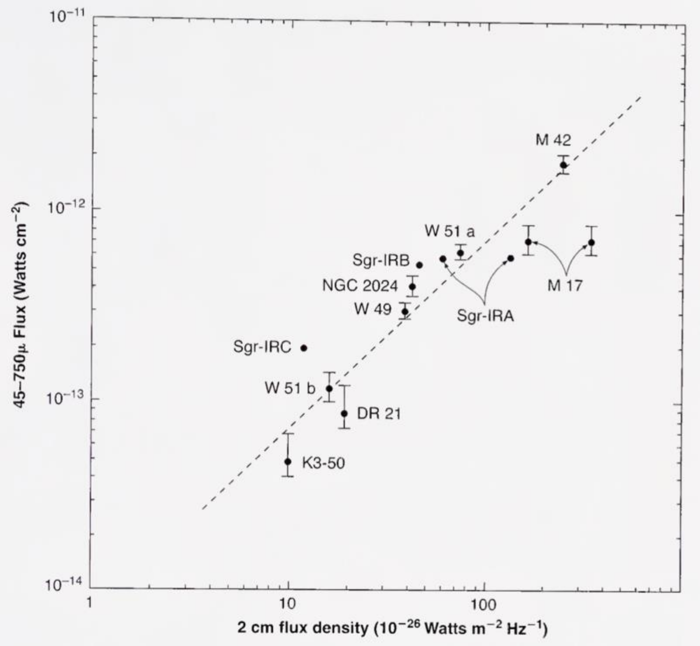
・important for small particle whose temperature is affected by a single photon

・such infrared peaks are available for other H II regions

⇨these peaks are regions of high dust density close to high-luminosity stars

・absorb the energy and reradiate by the solid particles

Origin of infrared emission



・the measured infrared flux is roughly proportional to the measured radio-frequency flux

・the radio-frequency flux from a nebula is proportional to the number of recombinations

⇨the infrared emission is roughly proportional to the number of recombinations

・plausibly interpretation

・ionization by a stellar photon in an optically thick nebula

→a recombination and the emission of an Ly α photon, or of two photons in the $2^2S \rightarrow 1^2S$ continuum

→Ly α photons are scattered many times by resonance scattering before escape

→perhaps every Ly α photon is absorbed by dust in the nebula and its energy is re-emitted as infrared radiation

⇨the ratio of total infrared flux to radio-frequency flux:

$$\frac{j_{IR}}{j_\nu} = \frac{n_p n_e \left(\alpha_B - \alpha^{eff}_{2\,^2S}\right) h\nu_{L\alpha}}{4\pi j_\nu}$$

・j: emission coefficient

・j_ν, α_B, $\alpha^{eff}_{2^2S}$ depend only weakly on T, and j_ν, j_{IR} have the same density dependence

⇨ratio is quite well determined

・ j_{IR}/j_ν from the observation data is higher than that from (7.13)

⇨the infrared emission is larger than that by absorption of Ly α alone

・in addition to Ly α , some of the stellar radiation with $\nu < \nu_0$ and the ionizing radiation with $\nu > \nu_0$ must be absorbed by the dust

⇨some of the ionizing photons are destroyed in this way

Dust in planetary nebulae

・dust in many planetary nebulae

・a continuum is ×10-100 stronger in the 5-18um region than the predicted free-free and bound-free continuum

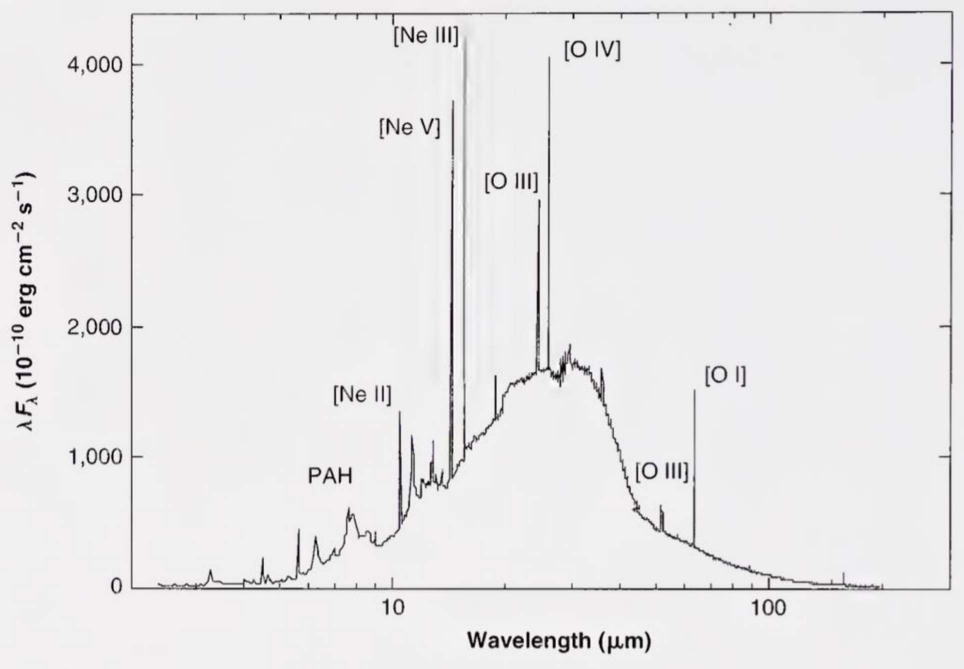
・observations at longer wavelengths (~100um) show that the infrared continuum peak at about 30um

→indicate $T_d \approx 100K$

→Figure 7.8: spectrum of NGC7027, the planetary nebula

・broad continuum is largely due to broad-band thermal emission by larger dust grains

・narrower features due to PAHs are prominent at shorter wavelengths



7.5 Formation and Destruction of Dust Particles
Formation of dust particles

- theoretical and experimental investigations
  - → ・dust particles can **grow by accretion of individual atoms from the interstellar gas**
    - ・dust particles can't initially form by atomic collisions
  - ⇨ ・**dust must have been present in the atmosphere of the star**

    or

    - ・**dust must have formed during the earliest stages of the process**, at the high densities region close to the star
- outer layers of cool stars can be cool, dense, and predominantly molecular
  - ・H_2 and CO: the most common molecules
    - ・ if the abundance of O is greater than C in the outer layers of the star (as Solar system)
      - ・nearly all C→CO
      - ・rest O→other molecules→the silicate grains
    - ・if the abundance of C is greater than O
      - ・Graphite is formed by rest C

Destruction of dust particles

・**sputtering**

- ・collisions of ions with a dust particle knock atoms or molecules out of its surface
- ・important if the gas is quite hot, but inefficient at nebular temperatures

・**the ejection of photoelectrons**

- ・by absorption of high-energy photons
- ・when the potential due to the positive charge come to exceed the binding energy of the grain, grain is destroyed

・**sublimation**

- ・if a grain becomes hot, outer layers will evaporate and the grain is destroyed

⇔observation shows that elements like Al and Ca (mostly found within grains in ISM) are also strongly depleted from the gas phase in nebulae

⇨these processes are not efficient to destroy a significant fraction of the grains

・**shock waves**

- ・at near the shock front, process such as grain-grain collisions and sputtering occur

→larger grains are broken into smaller ones with a range of sizes

- ・probably establishes the observed distribution of sizes
- ・observed variation in the ratio of total to selective extinction is partly due to different regions with different histories of shock passage, and a different size ratio of grains