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Broadening of stellar spectral lines due to the thermal motion of atoms

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ABSTRACT

The only information we receive from the stars is their radiation. By studying this radiation with the help of spectroscopic methods we can be familiarised with the physical characteristics of stars. One of the extremely important tasks of spectroscopy is to study and analyse the spectral line profiles. Astrophysics observes starlight, i.e. the frequency of the light, which implies the application of the Doppler effect on electromagnetic waves. Doppler broadening of spectral lines is the consequence of thermal, chaotic motion of atoms (absorbers/emitters). It is the result of the Doppler effect, i.e. the apparent change of the absorbed radiation wavelength in relation to the radiation wavelength absorbed/emitted by the atom moving relative to us as observers. In case of thermal motion, in the approximation of the local thermodynamic equilibrium, we deal with the Maxwell distribution. Maxwell distribution of molecules by velocities is a Gaussian curve identical to the intensity distribution in Doppler broadening. We will demonstrate that the half-width of spectral lines is directly proportional to the temperature and wavelength, and inversely proportional to the emitter's mass. This means that, for heavier emitters (higher atomic number), the broadening of lines arising from the Doppler effect will be less pronounced, but it will be more prominent for warmer stars.

Keywords: Doppler broadening, Kinetic theory of gases, Spectral analysis in astronomy, Line spectrum, Stellar spectrum

Kinetic theory of gases

Starting from a simple model, the kinetic theory of gasses quantitatively describes the behaviour and properties of gasses, connecting the macroscopic properties of gasses (e.g. pressure and temperature) with their microscopic properties (e.g. mass, diameter and velocity). It allows constructing an equation of state, molecular velocity distribution, and gas heat capacity values without considering the quantum effects, and, among other things, it also enables us to understand thermodynamic properties on a molecular level. Through efficient collision cross sections, it enables us to calculate the number of collisions and the mass and energy velocity distributions, as well as the angular momentum for the ideal gaseous state.

Gas molecules have a chaotic motion in all the courses and directions. Each of the gas molecules moves with a certain velocity intensity, and each one's velocity changes in time. In addition, a change in velocity also occurs after a collision with the walls of a container when their speed depends upon the intensity and velocity direction before the collision. Even if all the molecules had the same velocities before the collision, they will subsequently have diverse velocities, especially since the small gas volume contains a large number of molecules, so the collision frequency is greater. In 1860, Maxwell concluded that, regardless of the disorganised movement and diverse velocity values of the molecules, there is still a proper distribution of molecules by velocity.

Using statistical methods, he deducted a law of molecule distribution by velocities. Molecule distribution by velocities depends upon temperature. Heating gas increases the kinetic energy, i.e. molecular velocity. Based upon the distribution function, we will notice that when the temperature increases, the value of the most probable velocity also increases, but the number of molecules having precisely that velocity decreases. In addition, heating increases the number of molecules with large velocity values. This new representation did not signify a rejection of the previous thermodynamic concepts, but a better basis for thermodynamics in explaining observations and experiments. In real gasses, the velocities of individual molecules encompass a wide area, with constant collisions which continually change the molecular velocities. Maxwell has demonstrated that the distribution of molecules by velocities can be shown through an analytic equation:

$$\frac{dw}{dv} = 4\pi \left(\frac{m}{2\pi k_B T}\right)^{3/2} v^2 e^{-mv^2/(2k_B T)}$$

Spectral analysis in astronomy

The main source of information on objects outside the Solar System is their light that reaches Earth. Since light represents electromagnetic waves, based upon electromagnetic radiation emitted from or reflected off celestial bodies, we can obtain data regarding the position, movement of celestial bodies, their chemical composition, temperature, etc. Distribution of radiant energy over wavelengths in the stellar spectra is specified in Wien's displacement law.
Intensity and the profile of the spectral line depend upon various factors such as:

• temperature - determines the wavelength

• particle concentration determining the Doppler broadening of the spectral line

• the strength of the present magnetic and electric fields which cause the Zeeman effect and Stark broadening

• the macroscopic movements in the object

Identifying the chemical composition of cosmic objects is performed by comparing their line spectra with the laboratory-obtained spectra of the known elements. This method is called spectroscopic or spectral analysis of the celestial body, implying the determination of the celestial body's main characteristics on the basis of comparing electromagnetic radiation emitted from the body with the emission and absorption spectra of the known substances. Spectral analysis is a contactless method enabling the identification of the cosmic substance's chemical composition.

Line spectrum

The emission line spectrum occurs by emitting photons from the stimulated electrons during de-excitation in superheated gasses. As opposed to the continuous spectrum, the line spectrum occurs in greatly-diluted gasses. Radiation that is then emitted represents the radiation in the form of bright emission lines corresponding to the atoms of a substance. The lines are superposed on the continuous radiation generated simultaneously. The line spectrum, i.e. the intensities, positions and mutual distances between its lines provide specific characteristics of each atom. One atom emits or absorbs photons of the same wavelength. Atomic spectra of a certain element created in the Cosmos must coincide with the laboratory-obtained spectra of the same atoms.

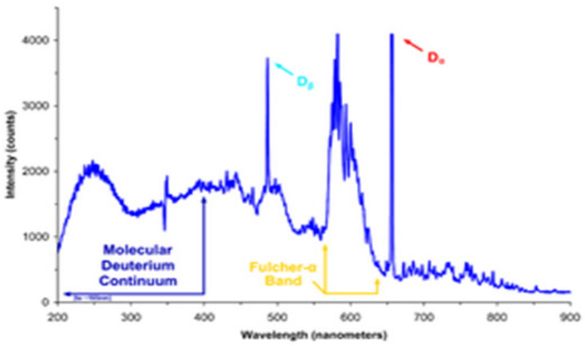

Image 1: Balmer lines α and ß are clearly visible in the continuous emission spectrum of radiation.

Stellar spectrum

For stars, the continuous spectrum is emitted from the photosphere, i.e. a star's outer shell.
The absorption spectrum occurs in the colder layers of a star's atmosphere, in the cold clouds of the interstellar gas or in the planet's atmosphere.

At the continuous spectrum of the photosphere we can, in certain cases, detect bright emission lines when the continuous radiation passes through the layers of atmosphere which are warmer than the photosphere.

The Doppler effect

The Doppler effect is the appearance where, due to the radial movement of emitters in relation to an observer, there is an apparent change of the emitted wavelength towards the red (in case the emitter is moving away) or towards the blue (in case it is approaching) (Image 2). This effect enables us to calculate the emitter's radial velocity.

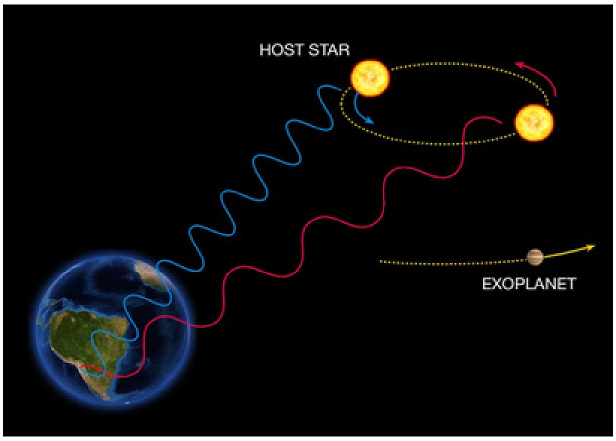

Image 2: Red and blue shifts.

A direct consequence of the Doppler effect is seen in the Doppler broadening of spectral lines occurring due to the thermal, chaotic motion of atoms in gasses, as well as because of the turbulent movement of atmospheric masses or gas clouds. In a substance, atoms move in different directions and at different velocities, and their kinetic energy depends upon the temperature of the matter.
This thermal, chaotic motion of atoms emitted at a certain wavelength results in the fact that the lines will have a certain width, i.e. they will be broadened towards the red (atoms moving away from us) and towards the blue (atoms moving towards us) in relation to the central frequency.

Thermal Doppler broadening

As previously stated, Doppler broadening is a consequence of the thermal motion of atoms (absorbers/emitters).

It is the result of the Doppler effect, i.e. the apparent change of the absorbed radiation wavelength in relation to the radiation wavelength absorbed/emitted by the atom moving relative to us as observers. At the moment of absorption/emission, some atoms move towards the observer and some move away from them, and the change, being negative in the first case, is positive in the second. Wavelength (frequency) displacement originating from the atom with a radial velocity of v_r is provided by the Doppler formula:

$$\frac{\Delta\lambda}{\Delta_0} = \frac{\Delta v}{\Delta_0} = \frac{v_r}{c}$$

Since radiation from a large number of atoms moving in different directions and with different vr is received, the broadening of spectral lines will occur. Even if atoms were to absorb/emit radiation only on a central frequency f=f0 in the line (neglecting the final width of the energy levels), the observer will perceive the radiation in its final frequency band.

Distribution of atoms by radial velocities is the Maxwell distribution described in detail in the previous chapter, represented by:

$$\frac{dn(v_r)}{n} = \frac{n(v_r)dv_r}{n} = \frac{1}{\sqrt{\pi}} e^{-v^2 r/\alpha^2} \frac{dv_r}{\alpha}$$

In order to calculate the Doppler broadening of lines occurring as a consequence of the particles' thermal motion, we will assume that the distribution of particle radial velocities is the Maxwell distribution, described in detail in the previous chapter:

$$n(v_r)\cdot dv_r = N\cdot\left(\frac{m}{2\cdot\pi\cdot k\cdot T}\right)^{\frac{1}{2}}\cdot e^{-\frac{m\cdot v_r^2}{2\cdot k\cdot T\cdot dv}_r}$$

where the most likely velocity is: $\alpha = \sqrt{\frac{2\cdot k\cdot T}{m}}$

The line width will then be equal to:

$$\frac{\Delta v_D}{v_0} = \frac{\Delta\lambda_D}{\lambda_0} = \frac{\alpha}{c} \qquad \Delta v_D = \frac{v_{0\cdot\alpha}}{c} = \frac{v_0}{c}\cdot\sqrt{\frac{2\cdot k\cdot T}{m}}$$

By observing the above formula, we can see that the Doppler width of spectral lines is proportional to the central frequency, resulting in the fact that the thermal Doppler broadening effect is more prominent in lines with higher frequencies.

In addition, Doppler width will be inversely proportional to the emitter's square root of mass, meaning that thermal broadening will be more pronounced in, e.g. a hydrogen atom than in an iron atom. This pattern is also confirmed by experimental research. E.g., the experimental research results for the Balmer H_6 line in the hydrogen spectrum. At the temperature of 50^0 C, $\Delta\lambda$ = 4.7 pm was experimentally determined, while, according to the previous form, we receive $\Delta\lambda$ = 4.2 pm.

By connecting the stated formulas, we receive:

$$\frac{dn(v)}{n} = \frac{1}{\sqrt{\pi}} \cdot e^{-\frac{\Delta v^2}{\Delta v D^2}} \cdot \frac{dv}{\Delta v_D} = \varphi_V^D \cdot dv$$

Where:

$$\varphi_v^D = \frac{1}{\sqrt{\pi} \cdot \Delta v_D} \cdot e^{-\frac{(\Delta v)^2}{\Delta v_D}}$$

We can see that the obtained profile of the broadened line is a Gaussian profile, as opposed to the collisional and natural broadening obtaining a Lorentzian profile.

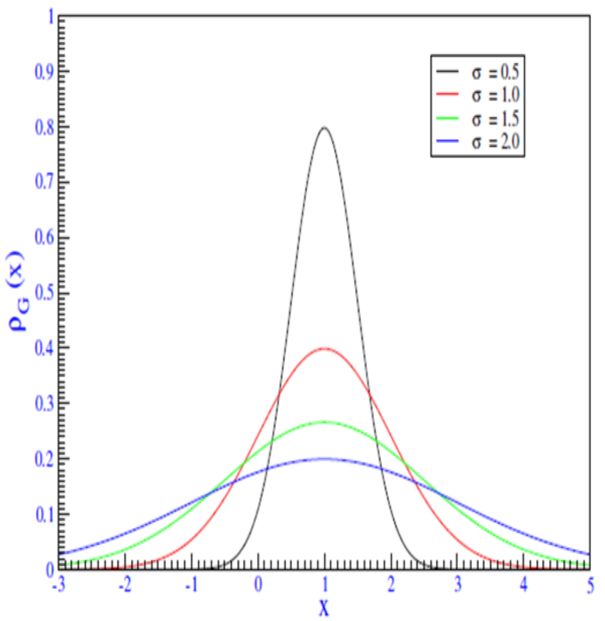

Image 3: Probability density function $f(vx^2)$ for two different temperatures.

Doppler broadening is, apart from the thermal, chaotic motion of particles, created by turbulent motion of substances.

Turbulent Doppler broadening

Turbulence represents a collective motion of a group of atoms and it is divided into microturbulence and macroturbulence.
In case of microturbulence, moving gas elements are smaller than the thickness of the entire region where the line is formed. Just like thermal broadening, microturbulent broadening provides a Gaussian line profile and the resulting effect on the line profile under the influence of the two processes would be a Gaussian, incurring through the convolution of two Gaussians. Microturbulent broadening is, just like thermal broadening, proportional to the central frequency, but unlike thermal broadening, it does not depend upon the emitter's mass.

Macroturbulence is the occurrence resulting from moving gas elements that are larger than the region in which the line if formed. In this case, a line is formed within each of the gas elements, and the observed profile will be a superposition of the profile related to the line emitted from all gas elements, while the line width will result from the movement of gas elements in different directions.

The appearance of line asymmetry in macroturbulent broadening enables us to study the kinematic properties of the emitting gas region.

Conslusion

By studying this radiation with the help of spectroscopic methods we can be familiarised with the physical characteristics of stars. One of the extremely important tasks of spectroscopy is to study and analyse the spectral line profiles.

The kinetic theory of gasses quantitatively describes the behaviour and properties of gasses, connecting the macroscopic properties of gasses (e.g. pressure and temperature) with their microscopic properties. The Doppler effect is the appearance where, due to the radial movement of emitters in relation to an observer, there is an apparent change of the emitted wavelength towards the red (in case the emitter is moving away) or towards the blue (in case it is approaching). This effect enables us to calculate the emitter's radial velocity. Turbulence represents a collective motion of a group of atoms and it is divided into microturbulence and macroturbulence.

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Širenje spektralnih linija zvijezda uslijed termičkog kretanja atoma

SAŽETAK

Jedina informacija koja nam dolazi sa zvijezda predstavlja njihovo zračenje. Proučavanjem ovog zračenja spektroskopskim metodama, možemo se upoznati sa fizičkim karakteristikama zvijezda. Jedan od veoma važnih zadataka spektroskopije predstavlja proučavanje i analizu profila spektralnih linija. U astrofizici se posmatra svjetlost zvijezda, odnosno frekvencije te svjetlosti, što podrazumjeva primjenu Dopplerovog efekta na elektromagnetne talase. Doplerovo širenje spektralnih linija je posljedica termalnog, haotičnog kretanja atoma (apsorbera/emitera). Rezultat je Doplerovog efekta, tj. prividne promjene talasne dužine primljenog zračenja u odnosu na talasnu dužinu zračenja koje apsorbuje/emituje atom koji se kreće u odnosu na nas kao posmatrača. U koliko je riječ o termalnom kretanju, u aproksimaciji lokalne termodinamičke ravnoteže raspodjela je Maxwellova. Maxwellova raspodjela molekula po brzinama je Gaussova kriva i identična je kao raspodjela intenziteta kod Doplerovog širenja. Pokazat ćemo da je poluširina spektralnih linija direktno proporcionalna temperaturi i talasnoj dužini a obrnuto proporcionalna masi emitera. Što znači da će za teže emitere (veći atomski broj) širenje linija uslijed Doplerovog efekta biti manje izraženo dok će za toplije zvijezde ono biti izraženije.

Ključne riječi: Dopplerovo širenje, Kinetička teorija gasova, Spektralna analiza u astronomiji, Linijski spektar, Spektar zvijezda

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