Optical forces as a redshift mechanism: the “Spectral Transfer Redshift”

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Abstract

The redshift observed in astronomy is explained by optical forces on electrons and atoms present in the intergalactic medium. The forces occur as a result of momentum exchange between light and matter. This produces an exchange of energy where the intergalactic medium is heated and the radiation is redshifted. The spectra of different light rays interact in the intergalactic medium to produce a spectral transfer redshift. Two mechanisms are examined: the dipole force which acts on atoms, and the ponderomotive force which acts on electrons. The dipole force produces a redshift which is wavelength dependent and can be distinguished from a Doppler redshift. The ponderomotive force produces a redshift which is independent of the wavelength and mimics a Doppler redshift. Both forces arise from a stimulated emission process which preserves the direction of propagation of one of the two interacting photons, a necessary condition to avoid blurring of images. This property distinguishes the spectral transfer redshift from all other redshift mechanisms proposed so far[1].

1 Introduction

Several models have been proposed to explain the observed redshift of cosmological objects. Some models are based on linear effects which transfer momentum between atoms and photons to produce the redshift. These mechanisms inevitably involve a transverse momentum given to the photons, resulting in blurred images. This eliminates them as possible candidates for redshift mechanisms. Other models are based on nonlinear effects such as stimulated Raman and stimulated Compton scattering. Although these mechanisms do not blur images, they require luminous intensities that are much larger than what is generally encountered in intergalactic space. Finally, some proposed models are in contradiction with laboratory experiments. They require accepting spontaneous creation of matter or energy, unobserved quantum mechanical effects, or speeds that are faster than the speed of light and other incompatibilities with general relativity. So far, no model has proposed a satisfactory mechanism to explain the redshift. There is however an experimentally demonstrated mechanism[1] which is linear in intensity and maintains the direction of propagation of light rays as a result of an interaction with atoms and electrons. It is encountered in two different types of experiments: laser trapping of cold atoms via the “dipole force” and electrons manipulation via the “ponderomotive force”. These mechanisms are presented here to explain how the energy of photons is reduced as a result of interactions with the intergalactic medium. The mechanisms do not blur the images of distant objects and have a sufficiently large cross section to become appreciable at the very low matter density and light intensity encountered in interstellar and intergalactic environments.

The dipole force and the ponderomotive force arise when two, non-parallel light beams interact to produce an intensity gradient at the location of a particle. One photon is transferred from one beam to the other by a stimulated emission process[2, 3]. The change of the total momentum of the photon field results in momentum and energy gained by the atoms. As light is transferred into the lower energy beam every time there is an interaction, the mechanism produces a redshift of the radiation field. The effect is linear in the intensity of the light[1] so it remains significant, even at the low intensities encountered in intergalactic space. Because the redshift is caused by the interaction of light rays having different spectra, the mechanism is referred to as the spectral transfer redshift.

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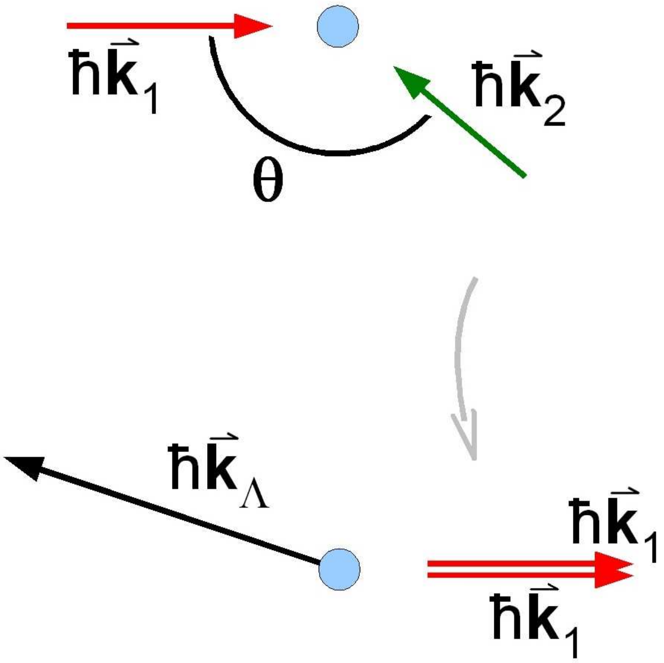

Figure 1: Scattering a photon via the optical force. When a 'red' photon $\hbar\vec{k}_1$ and a 'green' photon $\hbar\vec{k}_2$ interact with an atom at rest, the scattered photon is slightly redshifted by $\delta\nu$ and emitted in the same direction as the incident red photon. The net result is to increase the intensity of the red beam without changing its direction of propagation.

A description of the optical force is given in Section 2 for both dipole and ponderomotive forces. A quantitative comparison is made with Thomson scattering to show that the optical forces have a much larger cross section. A few applications of the spectral transfer redshift are given in Section 3 with quantitative evaluations of the magnitude of the redshift in various situations.

2 Theory of Optical Forces

Two types of optical forces on atoms and electrons are described: the dipole force and the ponderomotive force. The frequency shift, the scattering rate and the cross sections are calculated for the two types of forces as well as for Thomson scattering. A short explanation is given to explain why the effect is mitigated by high collisional rates.

2.1 Frequency Shift

Optical forces are the result of momentum exchange between photons and particles. As a result, photons are scattered in different directions with a change of their energy. Figure (1) shows a particle initially at rest interacting with two photons. The photon denoted by its momentum $\hbar\vec{k}_1$ is left unchanged by the interaction. The other photon $\hbar\vec{k}_2$ is scattered by an angle θ. Energy and momentum conservation require that for each scattering event, the relative frequency shift is:

$$\delta z = \frac{\delta\lambda}{\lambda} = \frac{-\delta\nu}{\nu} = \frac{h\nu}{mc^2}\sin(\theta/2) \qquad (1)$$

where m is the mass of the particle. With visible light at $\lambda = 550$ nm the frequency shift is $\delta\nu_H = 1.3$ MHz for a hydrogen atom and $\delta\nu_e = 2.4$ GHz for an electron, corresponding to a maximum redshift per scattering event $z_H = 2.4 \times 10^{-9}$ and $z_e = 4.4 \times 10^{-6}$ respectively. Because of the $\sin(\theta/2)$ term which is null for forward propagation, this type of interaction has often been rejected as an explanation of the redshift. However, a redshift compatible with astronomical observations is possible if stimulated emission is involved in the interaction.

2.2 The Dipole Force

The dipole force results from the interaction of an atom with a standing electromagnetic wave[1]. Two light beams with an electric field $E_{0i}\cos(\vec{k}_i \cdot z - 2\pi\nu_i t)$ ($i = 1$ and 2) coming from different directions produce a field with an intensity gradient. The atom is polarized by this field with a polarization energy proportional to the intensity of the field. The polarization energy is $U(\vec{x}) = -\alpha E_{01}E_{02}\cos(\vec{k}_\Lambda \cdot \vec{x})$, where $\alpha = \mu^2(\nu_0 - \nu_i)/h$, ν_0 is the resonance frequency of the atom (a two level atom is used in this simplified model), and $\vec{k}_\Lambda = \vec{k}_1 - \vec{k}_2$. The spatial variation of the polarization energy results in a net force on the atoms $\vec{F} = -\alpha\nabla E^2(x) = -\alpha E_{01}E_{02}\sin(\vec{k}_\Lambda \cdot \vec{x})\vec{k}_\Lambda$. Quantum mechanics describes this force as resulting from photon $\hbar\vec{k}_2$ at a frequency ν_2 interacting with the atom already polarized by another photon at a slightly lower frequency $\nu_1 = \nu_2 - \delta\nu$. The photon is scattered at the lower frequency ν_1 by a stimulated emission process[2, 3]. The photon's change of momentum and energy is transferred to the atom which experiences the force. After the interaction, both photons have the frequency ν_1 and have exactly the same direction as a result of the stimulated emission process[4]. The emission of the second photon in the same direction as the incident photon of frequency ν_1 changes the intensity of beam $i = 1$ but maintains its directionality. It is important to realize that all scattered photons are emitted in the direction of an already existing light beam.

The scattering rate required to produce the force is

$$\nu_s = \frac{2\alpha_F d^2}{h|\nu - \nu_0|}\sqrt{I_{01}I_{02}}, \tag{2}$$

where $\alpha_F \approx 1/137$ is the fine structure constant, $I_{0i} = c\epsilon_0 E_{0i}^2/2$ is the intensity of the i^{th} light beam, and d is the dipole moment displacement of the atom. For hydrogen $d \approx a_0 \approx 5.2 \times 10^{-11}$ m.

2.3 The Ponderomotive Force

In the case of the ponderomotive force on an electron, the electron in an electromagnetic field is accelerated and also reacts to its own field. The force is also a result of photon scattering[3]. As was shown for the dipole force photon $\hbar\vec{k}_2$ interacts with the electron already in the field of another photon at a slightly lower frequency ν_1. The photon is scattered at the lower frequency ν_1, also by a stimulated emission process. The scattering rate for the ponderomotive force is given by

$$\nu_s = \frac{\alpha_F}{4\pi^2 m\nu^2}\sqrt{I_{01}I_{02}}.$$

The frequency dependence of this expression does not contain a resonant term because the electron does not have an internal resonance frequency.

For $I_{01} \approx I_{02}$, the scattering cross section for the ponderomotive force on an electron is

$$\sigma = \frac{\alpha_F h}{2\pi m_e \nu} = 8.45 \times 10^{-7}/\nu, \tag{3}$$

which for light at $\lambda = 550$ nm is $\sigma \approx 1.54 \times 10^{-21}$ m^2. If a density of 2.5 electrons per cubic meter is assumed, there will be an interaction every 8 kpc on average.

2.4 Thomson Scattering

The Thomson scattering cross section is evaluated for comparison with the mechanisms described above. The frequency shift caused by Thomson scattering off an electron is the same as given by Eq. (1) above. At high energies, the cross section is given by the Klein-Nischina formula (Compton scattering). For photons in the visible the effect reduces to the classical Thomson scattering with a cross section $\sigma \approx 6.7 \times 10^{-29}$ m^2. This value is more than a million times smaller than the cross section calculated above for the ponderomotive force. This explains why redshift mechanisms based on Thomson or Compton scattering[5, 6] do not contribute significantly to the redshift.

2.5 Effects of collisions

If collision are present, atoms or electrons interact collectively as particles with higher effective masses. When the collision rate exceeds the frequency shift, the Lamb-Dicke effect[7] produces sidebands outside the recoil frequency and the scattering rate is significantly reduced. Experiments in the Lamb-Dicke regime are often used for high resolution spectroscopy because the recoil shift is eliminated at higher pressures. At 760 Torr and a temperature of 273 K, there are 9×10^9 collisions per second in H_2 and no recoil is possible. A pressure below ~ 0.15 Torr (the pressure above an altitude of ~ 75 km) is required for the redshift mechanism to occur. This is why no redshift is observed in the Earth's atmosphere.

3 Applications

The frequency shift of a photon interacting with the intergalactic medium increases with the number of interactions. The redshift after a traveled distance r depends on the density of the medium, the frequency shift at each interaction and the cross section of the process. The functional dependence is derived below for the dipole force in atomic hydrogen and for the ponderomotive force in electrons.

3.1 Redshift dependence on Distance

For the dipole force in atomic hydrogen, the redshift as a function of distance is given by the product of the frequency shift Eq. (1), the cross section from Eq. (2) and the density ρ:

$$\frac{\partial z}{\partial r} = \frac{2.4 \times 10^{-44}}{\lambda(\lambda - \lambda_0)} \rho \sin(\theta/2).$$

The function has a strong dependence on the wavelength, especially near the Ly-α resonance $\lambda_0 = 121.5$ nm. The resonant term implies that near the resonance, a strong redshift will occur which may result in the Ly-α forest observed in quasars. The redshift is weaker for longer wavelengths. At 550 nm, $\partial z = 5 \times 10^{-32} \rho \sin(\theta/2) \partial r$.

For the ponderomotive force, the redshift is obtained from Eqs. (1) and (3):

$$\frac{\partial z}{\partial r} = 1.1 \times 10^{-26} \rho \sin(\theta/2).$$

In this case, there is no dependence on the wavelength of light since the redshift is proportional to the frequency of the radiation and the cross section is inversely proportional to the frequency. Thus, the redshift mechanism produces a redshift similar to the Doppler effect.

3.2 Cosmic Microwave Background

When atoms and electrons at rest are considered, the result is always a loss of energy by one photon, as was shown above. If the atom or electron is moving compared to a reference system, the photon can be scattered with an increase of its energy. A blue shift is therefore possible when the atoms or electrons have their own motion. If the atoms and electrons are at a temperature T, the photons will reach an equilibrium when they have a blackbody spectrum at the same temperature T. The spectral transfer redshift therefore explains the cosmological microwave background if the interstellar medium is at the estimated temperature of 2.725 K.

This effect was already considered by Zwicky in his model of a redshift produced by a gravitational interaction with masses in the universe. He described the properties of a redshift mechanism involving the interaction of light with moving matter: "The transfer of momentum from the light to the surrounding masses should be determined[...] The proper motions of these masses will play some rôle. Shifts of the spectral lines to the violet should indeed be expected for thermodynamic reasons if light is traveling through systems of masses with very high average velocities."[8] The spectral transfer redshift provides another way to couple radiation with matter. The equilibrium temperature is reached as a result of thermodynamics.

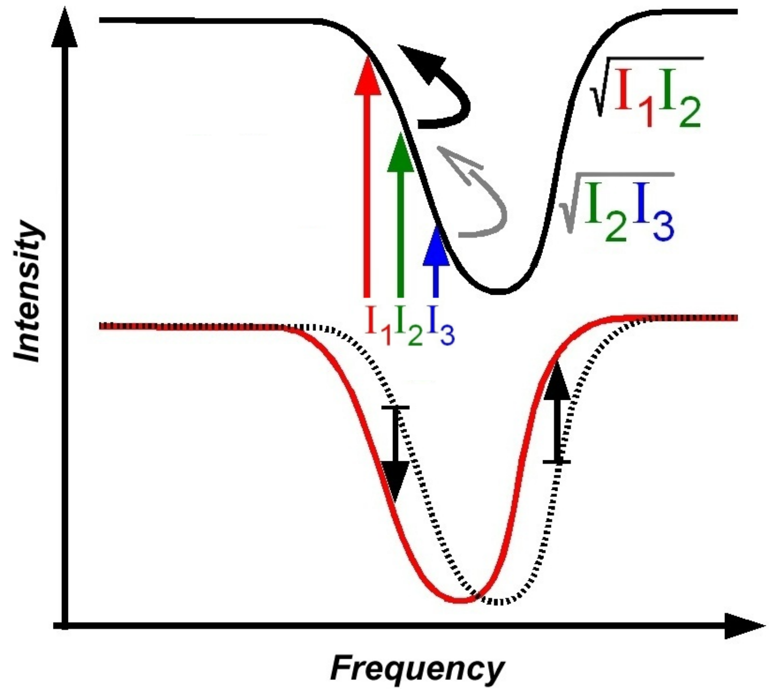

Figure 2: Spectral transfer mechanism. The intensity of the spectrum at I_2 is increased at a rate proportional to $\sqrt{I_2 I_3}$ but is decreased at a rate proportional to $\sqrt{I_1 I_2}$. The net change in intensity is proportional to the derivative of the intensity of the spectra of the interacting light rays. When all the intensity changes are considered, the result is a redshifted spectrum as shown by the solid red curve.

3.3 Spectral Transfer

Consider a bright object as seen from a distance where it has an angular size $\theta \approx 1$. The optical force on the medium surrounding the object remains significant due to the $\sin(\theta/2)$ term. The various rays interacting in the medium exchange photons with each other but maintain their direction. The effect of the optical force on the frequency of the light can be understood by considering a spectral feature, such as an absorption line, as is shown in Fig. (2). Consider the three intensities I_1, I_2 and I_3 of three nearby frequencies on the side of a spectral line. The optical force will increase the intensity I_2 at a rate r^+ proportional to $\sqrt{I_2 I_3}$ as given in Eq. (2). This is a result of the photons from I_3 being transferred to the beam of lower frequency I_2. The optical force will however decrease the intensity I_2 at a rate $r^- \propto \sqrt{I_1 I_2}$ because the beam I_2 is at a higher frequency than I_1. Since $r^- > r^+$, the net intensity I_2 will decrease. In general, the intensity will change at a rate proportional to the derivative of the spectral intensity with respect to the frequency. Since a change as a function of time is proportional to a change as a function of distance traveled by the light, the intensity change is:

$$\frac{\partial I}{\partial r} \propto \frac{\partial I}{\partial \nu}. \tag{4}$$

An intensity change that is proportional to the derivative of the intensity produces a shift of the spectrum towards the lower frequencies similar to a Doppler shift. This can be seen on the lower part of Fig. (2). This effect is the key to understanding this redshift mechanism. Because of the continual exchange of photons between the spectra of different rays, this mechanism is called the spectral transfer redshift.

An example of this occurs in the solar limb redshift. The larger redshift near the limb is readily explained by the spectral transfer mechanism since light emitted from the sun near the limb travels at grazing incidence near the surface where: 1) the density of hydrogen is higher, and 2) the angle of interaction between photons causes a larger $\sin(\theta/2)$ term. A wavelength dependence of this redshift is observed in the solar limb, which indicates that light is interacting with atomic species, probably hydrogen.

When the angular size of distant objects becomes very small, another source of light is required to explain a large redshift. Light emitted by the distant object is also scattered by other processes, although very weakly. The directional properties of the scattered light are not maintained, but it's spectral properties are. This diffuse light is thought to interact with the light from the distant object, and through stimulated emission, contributes to the redshift of the spectrum. This is how the spectral transfer mechanism maintains the image properties of a distant object while producing a redshift.

Solving Eq. (4) for the ponderomotive force, the redshift is

$$\frac{\partial z}{\partial N} = 1 \times 10^{-4}\ [\mathrm{m}^3/\mathrm{Mpc}]\ \sin{(\theta/2)},$$

where N is the column density. This redshift is equal to the cosmological redshift of $2.34 \times 10^{-4}/$ Mpc if the electron density is $\rho \sim 2.5\mathrm{m}^{-3}$. For regions of space where the density is uniform, the redshift will be proportional to the distance. However, near denser objects or in a universe with a fractal distribution of matter, the redshift deviates from a simple relation with distance. The spectral transfer mechanisms provides some hint to the cause of discordant redshifts. It also answers some objections to so-called errors in tired light cosmology[9].

A consequence of spectral transfer is that the spectrum of light emitted from our galaxy should be transferred to the light reaching us. Some spectral features that are slightly redshifted should be superimposed to the redshifted spectra of distant objects.

3.4 Redshift of a Blackbody Spectrum

An important property of the spectral transfer mechanism is the transformation of the blackbody spectrum. The spectral radiance at frequency ν_0 of a blackbody radiator at a temperature T_0 is described by Plank's law:

$$I(\nu_0, T_0) = \frac{2h}{c^2}\frac{\nu_0^3}{exp(h\nu_0/kT_0 - 1)}d\nu_0,$$

where $I(\nu_0, T_0)$ is given in $\mathrm{Wm}^{-2}\mathrm{sr}^{-1}$. The Doppler shifted spectrum of a blackbody radiator receding with a velocity v with a redshift z is also a blackbody spectrum:

$$I_{Doppler}(\nu, T, z) = \frac{2h}{c^2}\frac{\nu^3}{exp(h\nu/kT - 1)}d\nu,$$

where $T = T_0/(1+z)$ and $\nu = \nu_0/(1+z)$. This result is obtained using the Lorentz transform for relativistic speeds where the redshift satisfies $1+z = \sqrt{\frac{c+v}{c-v}}$. However with the spectral transfer mechanism, where the frequency of the light is decreased but the photon number remains constant, a redshifted Plank spectrum with an increased intensity is produced:

$$I_{ST}(\nu, T, z) = (1+z)\frac{2h}{c^2}\frac{\nu^3}{exp(h\nu/kT - 1)}d\nu.$$

This effect must be included for the Tolman surface brightness test for the reality of the expansion. In a steady-state universe older than current estimates, the brightness of galaxies is not subject to evolutionary models and cannot be used to explain the deviation from a Tolman signal $n = 4$[10].

4 Conclusions

In electrons, the spectral transfer redshift produces a redshift similar to the Doppler redshift: $z = \Delta\lambda/\lambda$ independent of λ. The mechanism also occur in atoms where there is a dependence on the wavelength. It is a linear process in intensity, which gives it a large cross section compared to other mechanisms such as stimulated Raman and stimulated Compton scattering. Because two photons are involved in a stimulated emission process, the spectral transfer mechanism maintains the image properties of the source without any blurring. Every interacting photon is emitted in the direction of an already existing beam. The effect is demonstrated in the laboratory in experiments on atom cooling. It can account for the Solar limb shift and the cosmological microwave background. A low density of the order of a few tens of electrons per cubic meter is enough to produce a redshift consistent with Hubble's constant. In regions of space where high densities of electrons or atoms are encountered, it could explain discordant redshifts. The mechanism can be seen as a thermodynamic exchange of the warmer radiation with the colder atoms, i.e. the atoms are heated by the radiation field. The cross section of the spectral transfer redshift is millions of times larger than Compton scattering. It does not have the problems of other non-Doppler mechanisms[11, 12] which require untested assumptions, are not tested experimentally, or do not produce large redshifts. The mechanism is now being studied for radiation going through the Van Allen belts where high densities of electrons are known to exist.

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