Photons, the essential tool of astronomers★

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Abstract: Photons are the carriers of most of the information that we have about the Universe outside the Solar System. The only exceptions are a few cosmic rays and several elusive neutrinos (at least until gravitational waves will be detected). Therefore photons are the essential tool of astronomers. I will discuss the kind of information which photons carry to astronomers (direction, energy, and polarization) and how this information might be changed during their travel across the Universe, with particular attention to the polarization angle, since such change would be connected to a violation of the Einstein equivalence principle, on which all metric theories of gravity are based, including General Relativity, for which we celebrate the centennial in this 2015.

Astronomy, an observational science

Astronomy is not an experimental science in the Galilean sense. In fact, we astronomers cannot carry out experiments to prove our theories. We can only observe what the Universe shows us. Therefore the photons, i.e. the *quanta* of light, are very important for us, since they are the carrier of almost all the information that we have about the Universe outside the Solar System. Although we can directly reach planets, satellites, asteroids and comets of the Solar System with spacecrafts and we can hope to explore them with manned missions, this represents a completely negligible fraction of the Universe ($\sim 10^{-45}$ in volume). From the Universe, in addition to photons, we receive also cosmic rays, i.e. energetic particles, and neutrinos. However, although the firsts are important for the understanding of high-energy phenomena, they are very few and the information they carry is very small in comparison with that carried by photons. The same happens with neutrinos: they are numerous, but very elusive, i.e. they interact very little with other particles and with photons, and therefore give us very little information. Gravitational waves, as predicted 100 years ago by Albert Einstein in his theory of General Relativity (GR), would give us important

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information about mass motion in the Universe. However they still have to be detected. Photons are therefore by far the main information carrier for astronomers. In this 2015, the International Year of Light, it is worth examining in more detail how useful is light for astronomers.

The astronomical information carried by photons

What type of information do photons carry? The answer is easy and simple: they carry information about: 1. the **direction** they come from (we code this with celestial coordinates), 2. their **energy** E, equivalent to the wavelength λ or the frequency ν of the associated electromagnetic radiation ($E = h\nu = hc/\lambda$), and 3. the **position angle of their polarization**. From these three simple pieces of information, added up for all the photons that we can detect, we derive most of what we know about the Universe.

Photons are also tools for special purposes in astronomy. For example, thanks to the Doppler effect, **photons are used to measure radial velocities**. This is because, if the source of photons is moving radially with respect to us observers at a velocity v (this velocity is positive if source and observer get further away, and is negative if they come closer together), the observed wavelenght λ_o is different from the emitted one λ_e by an amount $\Delta\lambda = (\lambda_o\text{-}\lambda_e)$ given by (c is the velocity of light, equal to 299.792,458 *km/s*):

$$\Delta\lambda/\lambda = v/c = \beta$$

if $\beta << 1$. Instead, if the relative velocity v approaches that of light, one has to use the relativistic formula:

$$\Delta\lambda/\lambda = -1 + \sqrt{(1-\beta)/(1+\beta)} = z$$

where z is the so-called redshift.

For example, the accurate measurements of small periodic variations in the radial velocity of stars have led to the discovery of most of the known extra-solar planets, since both star and planet rotate around their barycentre.

In addition, bacause of the expansion of the Universe, **radial velocities can be used to measure distances**, according to the Hubble law:

$$D = v/H_0$$

where H_0 is the Hubble constant. The Planck satellite has recently measured:

$$H_0 = 67.80 \pm 0.77 \ km/s/Mpc.$$

Thanks to the finite and constant speed of light, **photons are used to measure sizes**, since the distance travelled by photons in a given time interval can be exactly predicted.

For example, Supernova 1987A exploded in the Large Magellanic Cloud in February 1987. A few years later (Δt) a ring was discovered by the Hubble Space Telescope around the location of the explosion, due to the interaction of UV light emitted by the SN and the surrounding material. The radius of the ring is $R = c\,\Delta t$ (Panagia, 1998). Then, when you know the linear size R of the ring, you can determine its exact distance D, by comparing it with its angular size θ: $D = R/\theta$.

Again thanks to the finite and constant speed of light, **photons are used to see in the past,** but only along the past light cone. We astronomers use this property of photons to study the evolution of the Universe (galaxies, structures, etc.).
The Universe is 14 billion years old. The oldest photons we can see are those of Cosmic Microwave Background, which were emitted when the Universe was 380.000 years old. Therefore we can see the Universe when it had 2.7×10^{-5} of its current age: this is like seeing all the life of a 40 years old man, since he was 10 hours old.

Does the information carried by photons change?

In order to make the best use of the information carried by photons, an important question to ask is whether this information is changed while photons travel in vacuum across the Universe. Of the three basic informations carried by photons, we know that their direction can be changed by a strong gravitational field, which curves space-time, hence deflects photons. Also the energy of a photon is changed by the expansion of the Universe. Is the position angle of the polarization of a photon also changed in vacuum, i.e. is there any Cosmic Polarization Rotation (CPR)? The answer is “No” (see di Serego Alighieri 2015 for a recent review on CPR tests). The question of the existence of any CPR is interesting also for another reason: clearly CPR, if it exists, should be either positive, for a counter clockwise rotation (we follow the IAU convention for the polarization angle), or negative for a clockwise rotation. This immediately suggests that a non-zero CPR would be connected with the violation of fundamental physical principles.
Indeed CPR is connected with Lorentz invariance violation, CPT violation, neutrino number asymmetry, and violation of the Einstein Equivalence Principle (EEP), on which GR is based. In fact a null CPR greatly increases our confidence in GR. In this GR centennial year let’s examine in some detail why CPR is connected with a test of the EEP.

The equivalence principle equates a gravitational field and a uniformly accelerated frame (inertial mass = gravitational mass). It has been stated in various forms:

1. The weak equivalence principle (WEP, or Galilean EP) states the equivalence as far as the motion of free falling bodies is concerned. The WEP is tested to an accuracy of $\sim 10^{-13}$ by Eötvös type (torsion balance) experiments, and future space missions (STEP) would test it to 10^{-17}.
2. The EEP extends the equivalence to all experiments involving non-gravitational forces; all metric theories of gravity, including General Relativity, are based on the EEP. The EEP is tested to an accuracy of only $\sim 10^{-4}$ by gravitational redshift experiments.

Schiff (1960) has conjectured that any complete, self-consistent theory of gravity, which obeys the WEP, would necessarily also obey the EEP. If this were true, then the EEP would also be tested to an accuracy of 10^{-13}.
However Ni (1977) has found a unique counterexample to Schiff's conjecture: a pseudoscalar field φ that couples to electromagnetism in a Lagrangian of the form:

$$L = -1/(16\pi)\ \varphi\ e^{\mu\nu\rho\sigma}\ F_{\mu\nu}\ F_{\rho\sigma}$$

leading to a violation of the EEP, while obeying the WEP.
Carroll & Field (1991) have shown that, if such coupling were significant in a cosmological context, then the plane of polarization of light coming from very distant objects would be rotated during its journey across a considerable fraction of the size of the Universe, i.e. CPR angle $\alpha \neq 0$. Since such a rotation is not observed ($\alpha = 0$), we conclude that the EEP is not violated in this unique fashion.

Light and darkness

For us astronomers light exists, since it is made of photons (or electromagnetic radiation), which can be measured. On the other end, darkness is just absence of light, therefore does not exist. However a poet or just a man in the street would tell you that both light and darkness create sensations, that some of us like light, some like darkness. In this sense both light and darkness are real.
In trying to investigate this question in the light of this multidisciplinary conference, I have to admit that the information that light carries to us actually comes mostly from the contrast between light and no-light. You see a star in the night sky because the sky around it is dark. In fact, when the sky during the day is bright, you cannot see the stars. If the sky were completely bright, as foreseen by the Olbers paradox, the information content would be very small. The paradox,

stated by Olbers in 1823, says that a static, infinitely old Universe with an infinite number of stars distributed in an infinitely large space would be bright rather than dark. This is because the surface brightness (i.e. the luminosity per unit solid angle) does not depend on distance, since both the luminosity and the solid angle decrease as the distance squared. Everyone knows that this paradox is not true, since the sky is dark at night. This is because the Universe is not infinite in time and expands, therefore photons coming from very far lose energy.

Even if you consider the cosmic backround radiation (CMB), which comes from when photons decoupled from particles 380000 years after the Big Bang and could then travel to us undisturbed, most of the very important information that the CMB carries to us comes from the very small disuniformities (at the level of 0.001%) of this very uniform radiation.

At this conference I met a metaphysics philosopher, who gave an interesting talk about the relationships between Metaphysics, Science and Theology on the basis of the concept of being. He seemed to me the right person to ask if darkness exists. His answer was that only things exist, light and darkness are just accidents, attributes of things: as such they don't exist. In this way the panorama is complete: for poets both light and darkness exist, for scientists only light exists, for metaphysics neither exists!

What would a theologian say about this problem? The very beginning of the Bible is: "And God said, **"Let there be light," and there was light**. God saw that the light was good, and **he separated the light from the darkness**" (Genesis 1, 3). So God created light and separated it from darkness, he did not create darkness. Therefore theologians should hold the same view as scientists about the existence of light and darkness.

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