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Stellar and Extragalactic Radiation at the Earth's Surface

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Abstract. Reviving a calculation made by Eddington in the 1920s, and using the most recent and comprehensive databases available on stars and galaxies, including more than 2,500,000 stars and around 20,000 galaxies we have computed their total radiation received at the Earth just outside its atmosphere. This radiation density, if thermalized, would be equivalent to a temperature of 4.212 K. The comparability of this temperature to that of the cosmic microwave background (2.723 K) may either be a pure coincidence or may hold a key to some as yet unknown, aspect of the universe.

Key words. Stellar background—stars—CMBR.

1. Introduction

In 1926, Eddington made an order of magnitude calculation in which he estimated the total radiation background from stars in the Galaxy by assuming a population of only 2000 stars of apparent bolometric magnitude $m = 1.0$. He arrived at an energy density of starlight of around 7.67×10^{-13} erg cm^{-3}. If equated to a black body equilibrium distribution, this worked out to a temperature of ~ 3 K. Eddington identified it with the 'temperature of interstellar space', agreeing with an earlier calculation of Ch. Fabry that this was certainly an underestimation.

Today we have much better and far more comprehensive databases than those available to Eddington. Using them it is possible to redo the calculation which typically runs along the following lines.

2. The basic equations

The total radiation received from all directions by a square centimetre of surface area per second at the Earth will be denoted by

$$j = j_s + j_g \tag{1}$$

of which j_s is the radiation of N stars in the Galaxy (which also includes those in the Milky Way band) and j_g is the contribution of P external galaxies. The Sun is excluded from the first term and our Galaxy from the second.

To fix units we shall assume that a light source of *zero bolometric magnitude* ($m_{\rm bol} = 0$) gives an energy flux j_0 in the vicinity of the Earth, where

$$j_0 = 2.48 \times 10^{-5}\,\text{erg cm}^{-2}\,\text{s}^{-1} \tag{2}$$

as given by Allen (1999). Thus we can write the corresponding energy flux from a light source of bolometric magnitude m as

$$j(m) = j_0 \times 10^{-0.4m} = j_0 \times \text{dex}\,(-0.4\,m). \tag{3}$$

Assuming that we have a stellar distribution in which there are n_i stars of magnitude m_i, with $i = 1,\ 2,\ 3, \ldots$, we get

$$N = \Sigma_i\ n_i, \tag{4}$$

$$j_s = j_0\ \Sigma_i\ n_i \times \text{dex}\,(-0.4\,m_i). \tag{5}$$

Likewise for galaxies we shall write

$$P = \Sigma_i\ p_i, \tag{6}$$

$$j_g = j_0\ \Sigma_i\,p_i \times \text{dex}\,(-0.4\,m_i). \tag{7}$$

We will use these formulae in estimating the stellar and extragalactic contributions.

3. Stellar radiation

We have used the data given by the CDS, Strasbourg for $N = 2{,}552{,}323$ stars. The data are available in tables grouping stars in magnitude intervals of $\Delta m = 0.25$, either in BT or VT magnitudes. To be more rigorous and consistent, one should use only *one* magnitude (either B or V) and correct it properly for the bolometric correction (BC) derived from the colour indices.

However, there are some caveats. Firstly, we are ignoring the high frequency (UV, X, γ) radiation from active stars; this procedure therefore underestimates their radiative contributions. These are, however, negligible for our purpose here. We also note that most of the radiation lost by reddened stars is converted to heat or to excite the interstellar matter and is thus lost to us.

Secondly, we are using a catalogue that may not be complete for faint stars. Therefore while applying equation (5) we may have to correct the apparent luminosity function by a suitable extension to large magnitudes. This effect is, however, small and by not including it we may underestimate j_s by a very small amount.

Thirdly, the data list stars binned in intervals of 0.25 magnitude, with data on all stars brighter than $m = 0$ having been put together. This is corrected for in our calculation by taking data on individual stars with magnitudes up to $m = 2.5$. We do not expect different binning to produce a significantly different answer since the number–magnitude distribution is a fairly smooth function.

While calculating j_s from the tables, one needs to use a characteristic average value of m_i for the ith bin. The shape of the number–magnitude $n(m)$ curve helps in settling this issue. The curve for B-magnitudes has a linear rising trend for $4 < m < 11$, and a linear descending trend for $m > 14$. One may therefore write for each of the above ranges,

$$\Delta \log n(m) = k\Delta m, \quad k = \text{constant}, \tag{8}$$

where Δ relates to each typical interval $(m, m + 0.25)$. The average for this interval is then given by

$$\langle m \rangle = k^{-1} \log \left[\frac{\{\text{dex}\, km + \text{dex}\, k(m + 0.25)\}}{2} \right]. \tag{9}$$

To deal with the rather imprecise CDS statistics for bright stars, we have taken them individually to form a sample of 72 stars with magnitudes $m < 2.5$. We find that the total stellar contribution to the background is made up of set A: faint or moderately faint stars with $m > 2.5$ and set B: bright stars with $m < 2.5$. These add up to:

$$j_s = j_{sA} + j_{sB} = 1.782 \times 10^{-2}\, \text{erg cm}^{-2}\, \text{s}^{-1}. \tag{10}$$

4. Radiation from galaxies

Before considering external galaxies, it is necessary to note that among earlier authors, Pannekoek *et al.* (1949) had estimated the Milky Way contribution to the night sky background using out of focus photographic photometry. Although this value is not quoted by standard sources like Allen (1999), we give it here as a curiosity after correcting for BC:

$$j_{MW} = 1.529 \times 10^{-2}\, \text{erg cm}^{-2}\, \text{s}^{-1}. \tag{11}$$

Remarkably, this was close to our estimate (equation 10) obtained by stellar counts. We shall therefore assume that the Milky Way contribution is implicitly incorporated in equation (10) and proceed with this value in what follows.

For external galaxies we have used the catalogue of de Vaucouleurs *et al.* (1991). Dividing the 24 hours of right ascension into 24 sets we have used subsets of 10-minute interval each as representative samples. Then we have multiplied the figures for each magnitude interval by 6 and obtained an estimate of $p(m)$, the number of galaxies in a typical magnitude interval $(m, m + 1)$. A method similar to that used for stars but with $\Delta m = 1$, instead of 0.25, is used to estimate the average magnitude $\langle m \rangle$ for each interval. We have in all 19,822 galaxies in the magnitude range $m > 9$. We denote this set as set C. Additionally, there are bright galaxies with $m < 9$. We refer to the set of such galaxies with magnitudes in the range $9 < m < 20$ as set D, and we have taken the photographic magnitudes for these 15 galaxies as are given by Landolt and Börnstein (1965). Using these magnitudes requires a small bolometric correction, which we have ignored.

The total contribution from external galaxies is then

$$j_g = j_{gC} + j_{gD} = 3.467 \times 10^{-5}\, \text{erg cm}^{-2}\, \text{s}^{-1}. \tag{12}$$

Thus the total contribution from external galaxies is quite negligible compared to that from stars in the Milky Way.

5. Discussion of the errors

The first source of uncertainty which one can think of, is the existence of variable stars. As one has certainly counted them at their brightest phase, their contribution indicates an overestimation of the energy. However, it must be a very small error. According to our estimation, only about 10^5 variable stars exist in the galactic bulge of $> 10^{10}$ stars. Dropping them completely from the statistics would lead to an error on the energy of less than 10^{-5}. Another way to estimate more generally the number of variable stars is to evaluate the time which they spend as variable in their evolution, from 'birth' to extinction (as white dwarf or neutron star), during all their expected life time. Again, even for a star like the Sun, the first phase of its life (contraction from interstellar space) is of the order of 10^5 years against its stable life of about $> 10^{10}$ years. Its final stages of evolution towards the white dwarf stage is also very short (although one knows little about the time element). Evolution of the Sun might not be indicative of the more variable of the stars; but the variable star phase does not affect all stars; moreover it occupies a very little space in the colour–luminosity diagram of all observable stars, where the largest majority of observable stars are in their phase of stability, on the main sequence. The conclusion of our inquiry is therefore that variability of stars does not affect the energy received at the Earth by more than a factor 10^{-5}.

The existence of supernovae is also extremely small and hardly enough to alter our results. There is at the most 1 supernova per normal galaxy (such as ours) in 50 years; and it lasts schematically only a few months. Assuming a typical luminosity at its maximum of 10^{40} erg s^{-1}, assuming for it an average distance of 1 kpc, its energy flux at the Earth is 10^{-4} erg s^{-1} cm^{-2}, i.e., 100 times smaller than our estimates of the stellar energy flux at the Earth, and as this happens only during 3 months for every 50 years, this (statistically) diminishes its importance by another factor 10^2. Of course, supernovae may appear in other galaxies. The case of SN 1987A in the Small Magellanic Cloud is well-known: At a distance of 55 kpc, the flux at maximum phase was only 4×10^{-8} ergs s^{-1} cm^{-2}, i.e., 10^{-6} that of our estimate of the stellar flux at the Earth. Our conclusion here is that neglecting the SN in other galaxies affects the results at the 6th significant figure, and neglecting the SN of our own Galaxy affects them at their 4th significant figure. It is difficult to do a better estimation of the error, due to the random character of supernovae explosions; but it seems clear that neglecting them is perfectly allowed, and that our results are essentially not modified by this source of error.

The high energy radiation from the gamma rays, X-rays, and UV part of the spectra, is considered implicitly for 'normal' stars of a quasi-thermal behaviour. But there are strong UV, X-ray and gamma-ray emitters. Are they affecting our results? X-ray sources have been observed by several satellites. Estimating their number as $N = 105$, with a flux at the Earth of 10^{-11} erg s^{-1} cm^{-2} gives us a flux of the order of 10^{-6} erg s^{-1} cm^{-2}. About 100 gamma-ray sources have a still much smaller flux (10^{-4} MeV s^{-1} cm^{-2} per source) which amounts to 1.6×10^{-8} erg s^{-1} cm^{-2}. There is no estimate of UV sources that would not be either normal stars, or X-ray or gamma-ray sources. Altogether, the figures above indicate again that only the fourth significant figure of our estimate of the stellar flux at the Earth could thus be affected.

Nevertheless, the estimation we have made concerns only the present state of stellar and extragalactic radiation received **now** at the Earth. Clearly, this received radiation certainly varies during the life span of our Galaxy, even without considering the changes due to cosmological evolution of the environment of our Galaxy. This point becomes important as soon as we try to understand the background radiation of the Earth's sky.

6. Equilibrium temperature

Assuming that this radiation background were somehow thermalized, what black body temperature T would it produce? The answer is simple and is obtained by using the Stefan–Boltzmann law

$$\sigma T^4 = j_s + j_g. \tag{13}$$

For the value given by the equation (10) we find that $T = 4.212$ K. If we consider, however, a typical point in the intergalactic medium, far from our Galaxy, we need to use j_g only, as in equation (12) and get $T = 0.88$ K.

The comparability of the first value, 4.212 K to the temperature of the cosmic microwave background (CMB), namely 2.723 K makes one wonder if this is a pure coincidence. Perhaps this suggests a possible physical connection between starlight energy density and the energy density of CMB. It has already been noticed (for a recent discussion, see Hoyle *et al.* 2000) that if all of cosmic helium were processed in stars, the resulting starlight energy density would come very close to that of the CMB.

A cosmologist would point out that at a general point in the universe the coincidence of temperatures disappears and so any link with CMB is spurious. This is a possible position to take and it will certainly be taken in standard cosmology. Nevertheless, we feel that this modern reworking of Eddington's estimate of radiation background is of interest and may hold a key towards a deeper understanding of radiation backgrounds in the universe.

7. Conclusion and further research

Needless to say, our simple-minded result confirms that of Eddington's. It is important to note that we thus found a value of the equilibrium temperature quite of the same order of magnitude as that of the measured radiation of the microwave background, only slightly hotter. This rather good coincidence may be of a great significance.

However, before attempting any identification between our computations and the available observations, we have

- to compute, in the solar system, what can be the time scale of thermalisation in a very transparent medium,
- to explain why in this case, the thermalisation is not quite complete,
- to understand why the bipolar component could thus be explained, and
- to propose an interpretation of the fluctuations now attributed to fluctuations of the microwave background. We shall try to reply to these questions in the future.

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in all colours and all locations on the sky. We have not used the wealth of these data to their full extent, but we hope to use them to refine the present results.

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