HIGH ENERGY SOLAR RADIATION AND THE ORIGIN OF LIFE

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Abstract. Recent satellite observations of young, sun-like stars allow an estimation of the ultraviolet and X-ray radiation environment of the primitive Earth. Energy from these sources is found to be much higher than previously believed. We suggest that the influence of high energy radiation on the early development of life be reexamined.

1. Introduction

To synthesize the macromolecules necessary for the development of life requires an energy source. All discussions of this problem consider radiation from the Sun as one possible source, but most authors base their estimates upon observations of the present Sun (e.g., Miller and Urey, 1959; Miller and Orgel, 1974; Dickerson, 1978). At best, some consideration is given to the evolution of the sun from a cooler, less-luminous state (Fox and Dose, 1977), and the claim made that the present ultraviolet flux from the Sun is the highest it has ever been. The X-ray flux has been largely ignored. But the solar far ultraviolet and X-ray radiation is generated in the chromosphere and corona, and it has long been thought that the flux radiated from these layers was higher in the past. This idea originated with the observation (Wilson, 1963) that the emission cores of some optical absorption lines, one measure of chromospheric activity, are enhanced in the spectra of young solar-type stars. Skumanich (1972) first quantified the observation, showing that the strength of the emission cores in the resonance lines of Ca II (at 374 and 393 nm) is proportional to the inverse square-root of the age. This leads to the prediction that the ultraviolet and X-ray flux from the early Sun was higher than at present. Recent satellite observations of young stars confirm this expectation, and allow us to estimate the high energy radiation environment of the primitive Earth.

2. X-Ray Observations

Rocket observations of the last decade detected soft X-rays (0.3 – 6 nm) from a variety of peculiar stars. The systematic surveys made possible by the launching of the HEAO-2 (Einstein) satellite observatory have shown that X-ray emission is a common phenomenon for ordinary stars (Vaiana *et al.*, 1981). The high luminosities (up to 10^{32} erg/s, 2% of the solar luminosity) and shape of the spectra strongly suggest that hot (10^6 K) coronae are the source of the emission.

Our theoretical understanding of the structure and heating of the Sun's outer

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atmosphere is not good enough to allow reliable calculation of its radiative history. However, assuming the Sun's evolution is typical for stars of its mass and composition, we can reconstruct that history from observations of solar-type stars of younger age. Ages of individual, isolated stars are at present impossible to determine, but those within clusters can be dated from the theory of stellar evolution.

Stern *et al.* (1981) have recently surveyed 85 stars in the Hyades cluster, a moderately old ($5 - 9 \times 10^8$ yr) group at a distance of 45 parsecs. (All cluster ages are taken from the discussion of Barry *et al.* 1981). The typical X-ray (0.3 – 6 nm) luminosity of solar-type stars in the Hyades is 10^{29} erg/s, about 30 times that of the active solar corona at present. A younger cluster, the Pleiades (age $0.5 - 1.5 \times 10^8$ yr), is less well observed at present, because of its larger distance (130 pc), but about 20 sources have been detected in the luminosity range 10^{29} to 10^{30} erg/s (Ku, 1981).

Early in its history the Sun is likely to have been similar to the T Tauri stars (see Section 5). Studies of these stars are complicated by their large distances, and by the tendency of observers to focus on the more exotic members of the class. Walter and Kuhi (1981) considered a sample of T Tauri stars in the nearby Taurus-Auriga complex (distance 160 pc; age less than 5×10^6 yr), and determined that for stars brighter than apparent magnitude 13, the average X-ray luminosity is 1.5×10^{30} erg/s, with an rms scatter of a factor of two. Large X-ray luminosities, ranging up to 3×10^{31} erg/s, are also found in other young associations (Feigelson and DeCampli, 1981; Ku and Chanan, 1979; Chanan, 1981); young, solar-mass stars are probably well represented among these x-ray sources.

The observations of the youngest groups are not as complete as those of the Hyades, but we can nevertheless conclude that the the soft X-ray flux of the Sun was more than 10^{29} erg /s (30 times that at present) during the first half billion years of its life, and perhaps a factor of 10 to 100 more during the first 10 million years.

3. Far Ultraviolet Observations

The launching of the International Ultraviolet Explorer (IUE) satellite has made possible the routine observation of large numbers of stars. At present, however, the ultraviolet observations of young, solar-like stars are not complete enough to estimate the early solar radiation in the same way as above. We must instead resort to a more indirect technique, using correlations of ultraviolet intensities with other parameters which are known to depend on age.

The radiation from the present Sun at wavelengths between 30 and 150 nm amounts to about 2.1×10^{28} erg/s (Hinteregger, 1973; Thekaekara, 1973). About 70% of this energy is contained in one emission line, Lyman-α of hydrogen at 122 nm. Lyman-α is not directly measurable in faint, distant stars, both because of absorption by the interstellar medium and because of emission in the earth's geocorona. From analysis of the Sun, we know that most of the Lyman-α flux arises in the hottest parts of the chromosphere and in the so-called transition region (TR) between the chromosphere and corona (Avrett, 1981). Most of the rest of the flux from 20 – 150 nm is contained in the Lyman and helium continua, which are also radiated from high in the chromosphere. Ultraviolet lines arising in the chromosphere include those of Mg II, O II, Si II and C II. Emission lines formed in the transition region include those of Si IV, C IV, N V and He II.

Ayres *et al.* (1981) have obtained ultraviolet spectra (115–200 nm) of about 30 cool stars showing chromospheric emission. They find that the strength of the TR lines is highly correlated with the strength of the resonance lines of Mg II (at 280 nm), which are a major diagnostic of chromospheric activity. The dependence is not linear, however, with the TR line strengths increasing as a power of the Mg II line strength, with the exponent in the range 1.5–2.0. Lyman-α has been measured in six stars (Linsky and Ayres, 1978) and seems to increase linearly with the Mg II line strength, but these are giant stars, not very similar to the sun, and a more rapid increase for solar-type stars is not excluded. The Mg II lines are linearly correlated (Stencel *et al.*, 1981) with the classical chromospheric activity indicator, the resonance lines of Ca II (at 374 and 393 nm), and the latter are known to decrease with the square-root of the age (Skumanich, 1972). Therefore, assuming that Ly-α (and therefore most of the far ultraviolet flux) varies like other chromospheric and TR lines, we would expect the ultraviolet flux to decrease as a power of the age, with the exponent in the range 0.5–1.0. For the Hyades, then, with an age of 0.7 billion years compared to 4.7 billion years for the sun, we would expect the far ultraviolet to be enhanced by a factor of $(4.7/0.7)^{0.5}$ to $(4.7/0.7)^{1.0} = 3$ to 7.

Spectra of a few stars in the Hyades have been obtained with the IUE satellite. A very preliminary result for one star similar to the sun shows an enhancement of the C IV line (at 155 nm) by a factor of 20–30 with respect to the Sun (Zolcinski *et al.*, 1981), so the above scaling with age may be too conservative.

Further evidence for large amounts of ultraviolet radiation from young stars comes from observations of T Tauri stars, which show enhancements of transition region lines by factors of 100 to 10 000 (Gahm *et al.*, 1979; Imhoff and Giampapa, 1980).

We conclude that the Sun was brighter in the far ultraviolet during its first half billion years by at least a factor of 3 – 20. It may have been even more luminous, up to 10 000 times the present ultraviolet luminosity, during its first 10 million years.

4. Near Ultraviolet Observations

The near ultraviolet continuum (150 – 300 nm) arises from the upper photosphere in the Sun. Since the effective temperature of a low mass star generally increases during its Main-Sequence evolution, it might be expected that the near ultraviolet flux of the Sun would increase with time and that the present observed value is the highest it has ever been. However, it should be noted that input of additional mechanical energy in the deeper layers of a stellar atmosphere, where the temperature gradient is not steep, requires an increase in the rate of radiation to maintain energy balance. This results in a temperature above that expected from radiative heating alone (Avrett, 1981). It is conceivable that at a sufficiently high level of activity, the temperature of the upper photosphere could be raised significantly.

There is some observational evidence in favor of this idea. For example, the flux at 230 nm of RW Aurigae, a particularly active T Tauri star, is 15 times the solar value, even with no correction for interstellar extinction (Imhoff and Giampapa, 1980). Similarly, RU Lupi, another active T Tauri star, radiates 18 times as much as the sun does in the range 115 – 310 nm, most of it at wavelengths greater than 180 nm (Gahm *et al.*, 1979). These observations must be viewed cautiously, however, since the two stars are atypical of T Tauri stars, and may in fact have substantially higher effective temperatures. Unfortunately, no other near ultraviolet observations of young stars exist.

5. Was the Sun a T Tauri Star?

T Tauri stars are generally assumed to be low mass stars in an early evolutionary phase. A number of observations support this assumption: (1) T Tauri stars are associated with OB stars and/or molecular clouds, objects known to have ages less than 10^7 yr; (2) the spectra of T Tauri stars exhibit strong Li I (671 nm) absorption lines (lithium is rapidly depleted in young stars by convection carrying it to depths at which it is destroyed by nuclear fusion); (3) the correlation which exists between T Tauri positions and dust clouds would be destroyed in $3 - 5 \times 10^6$ yr (Herbig, 1970); and (4) Cohen and Kuhi (1979) located several hundred T Tauri stars on the Hertzsprung-Russell diagram, and by comparison with theoretical evolutionary models, showed that T Tauri stars have masses less than three solar masses, and ages less than 5×10^6 yr.

Early investigations did not find a clear distinction between the positions of T Tauri stars and other pre-Main-Sequence stars on the Hertzsprung-Russell diagram, and so it was surmised that perhaps only a fraction of young stars went through this stage of evolution. However, recent evidence strongly supports the conclusion that *all* low mass stars experience a T Tauri phase. The presence of enhanced chromospheric activity has been shown to bias spectral classification based on absorption lines (Calvet *et al.*, 1982). Proper classification of T Tauri stars now indicates that they are systematically cooler than other pre-Main-Sequence stars of similar luminosity (Rydgren, 1979; Cohen and Kuhi, 1979). Cohen and Kuhi found that in the cluster NGC 2264,43 of 45 pre-Main-Sequence stars without emission line spectra are hotter than spectral class K0 (effective temperature 5000 K), whereas 37 of 41 emission line (T Tauri) stars are cooler than this temperature. Selecting stars from an unbiased proper motion survey of NGC 2264, Calvet *et al.* (1982) confirmed the conclusion that T Tauri stars constitute the earliest optically visible stage of evolution for solar mass stars.

6. Conclusions

Our estimates of the X-ray and far ultraviolet radiation fluxes, averaged over the entire Earth, are given in Table I, along with estimates of other energy sources as compiled by Fox and Dose (1977). Most of the total solar radiation is at photon

TABLE I

Energy sources averaged over entire Earth (cal cm^{-2} y^{-1})

Type of energy	Contemporary Earth Age 4.7 × 10^9 yr	Earth at age 5 × 10^8 yr	Earth at age 10^7 yr
Total solar radiation	265 000	170 000	132 000
Far UV (20–150 nm)	1.4	4–30	100–10 000
X-Ray (0.3–6 nm)	0.2	7	70–700
Radioactivity from crust (35 km)	15.5	47	—
Heat from volcanic emission	0.15	>0.15	—
Electric discharges	4	4	—

energies too small to effect molecular changes, and the radioactivity in the Earth's crust is largely dissipated as heat below the surface, so electrical discharges and short wavelength solar radiation are usually considered as the major sources of energy for molecular evolution. As can be seen from the table, at present electrical discharges provide more energy than far ultraviolet or X-ray radiation from the Sun, but at an age of 5 × 10^8 yr the opposite was true, and at 10^7 yr both X-rays and the far ultraviolet were probably much stronger. How much of this radiation penetrates to the surface of the Earth depends on the composition of the primitive atmosphere, as does the nature of the chemical reactions in the atmosphere induced by the radiation. We believe that further studies of molecular evolution in the atmosphere and on the surface of the primitive Earth should take into account the higher level of solar X-ray and ultraviolet flux suggested by this study.

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