Soft X-Ray Background Flux

by

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Measurements of the soft X-ray background flux show good qualitative correlation with 21 cm measurements of columnar hydrogen density but too little apparent absorption. A portion of the flux may originate in unresolved population II objects or may be extragalactic.

RECENT observations of very soft cosmic X-rays[1-3] have been in serious disagreement about absolute intensity and interpretation. We now report the results of a rocket observation which seem to clarify the problem. The detectors, described below, were carried in an Aerobee 150 rocket launched at 0345 GMT on September 21, 1968, from White Sands, New Mexico.

Two proportional counters of 250 cm² area covered opposite directions perpendicular to the rocket spin axis. Each detector was surrounded on three sides by veto proportional counters separated from the X-ray counters by grids of 0·005 inch ground wires. Mechanical collimation limited the solid angle viewed to 0·019 steradians (2·6° × 23° f.w.h.m.). One counter was equipped with a 'Mylar' window (the material used by the Berkeley[1], Naval Research Laboratories[2] and Calgary[3] groups) while the other was equipped with a 2·4 micron polycarbonate 'Kimfol' window. The soft X-ray transmission of 'Kimfol' film is markedly better than that of the 'Mylar' (Fig. 1). Both the 'Mylar' and 'Kimfol' films were coated on their inside surfaces with about 20 μg/cm² of colloidal carbon. The carbon coating provided a conducting surface for reliable counter operation and also eliminated the sensitivity of the counters to ambient light. Light sensitivity is particularly serious with aluminium-coated thin films, presumably because the photoelectron work function of aluminium is small. Comparisons in flight with the response of ultraviolet photometers mounted on the same rocket by the Space Astronomy Laboratory of the University of Wisconsin verified that there was no significant ultraviolet contribution to the X-ray observations.

The open area of Fig. 2 shows the region of the sky scanned. The portion used for the analysis of the soft X-ray background radiation was between $b^{II} = -20°$, $l^{II} \approx 340°$ and $b^{II} = 40°$, $l^{II} \approx 160°$, including the south galactic pole and the galactic equator near Cassiopeia. No discrete X-ray sources are known in this part of the sky. The primary data telemetered to the ground were the number of detected counts in each of six differential pulse height channels. Expressed in terms of nominal X-ray energy, the pulse height channels corresponded to 0·15 to 0·48, 0·48 to 0·96, 0·96 to 1·6, 1·6 to 2·65, 2·65 to 6·5, and 6·5 to 8·4 keV. An on-board ^{55}Fe X-ray source was pushed into an exposed position once a minute throughout the flight and this verified that the gas flow system, counter gain and high voltage were operating stably to within 5 per cent in measured X-ray energy. Only data taken above 140 km were used.

Our analysis is similar to that described by Gorenstein *et al.*[4]. An assumed X-ray energy spectrum incident on the counter window is multiplied by the counter efficiency. Counter gas escape peak transfer effects, determined in laboratory tests, are taken into account and the result folded with the counter resolution. This folded distribution is integrated over the pulse height channel windows, and the predictions are compared with the observed response in the various channels. Data from the four higher energy channels should not and do not exhibit any significant variation with galactic latitude near the south galactic pole region, and both the 'Mylar' and 'Kimfol' counter data fit best an X-ray energy spectrum of the form $dE/E^{1\cdot 5}$. The fit to a 1·7 power law spectrum, appropriate at higher X-ray energies, is worse.

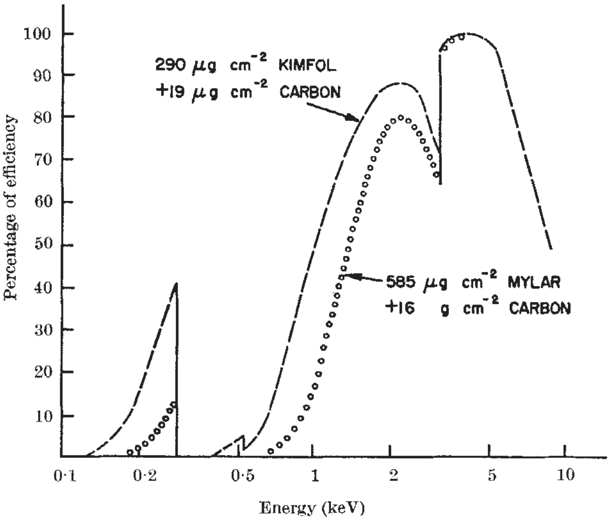

Fig. 1. Counter efficiencies versus X-ray energy. 'Kimfol' is $C_{16}H_{14}O_3$ while 'Mylar' is $C_{10}H_8O_4$. Both counters were filled to a pressure of 705 torr of the standard 90 per cent argon–10 per cent methane mixture.

The unguided but spinning rocket precessed very slowly and data from successive scans about the longitudinal or spin axis were combined. Fig. 3 shows these combined data for the first two pulse height channels of the 'Kimfol' window counter plotted against scan path in galactic latitude. (Data from the 'Mylar' window counter are similar, but the counting rates and statistical accuracy are smaller.) The data of the lowest energy channel show clearly the effects of interstellar absorption. The highest counting rate occurred near $b^{\mathrm{II}} = -60°$, $l^{\mathrm{II}} = 10°$, coincident with the region of lowest columnar hydrogen density derived from 21 cm line surveys in the southern galactic hemisphere.

The power law diffused X-ray flux observed above 2 keV is now known to be isotropic and presumably extragalactic in origin. A simple extrapolation of this flux, however, seems incapable of explaining our soft X-ray data. If, in spite of the clear observational evidence for interstellar absorption, we ignore such effects entirely and compute the expected counting rates in the first and second channels on the basis of an extrapolation of the $E^{-1\cdot5}$ power law, we predict rates of 9·9 counts per second and 6·6 counts per second respectively. If instead we extrapolate an $E^{-1\cdot7}$ power law, the corresponding rates are 14·6 per second and 7·7 per second. As is clear from Fig. 3, the predictions fall significantly below the observations. When interstellar absorption effects are included, we find that the expected rates vary with scan path in galactic latitude as shown by the dotted lines in Fig. 3.

In making these and other model predictions to be described later, we have used the interstellar X-ray absorption cross-sections of Bell and Kingston[5] and the columnar hydrogen density (N_{H}) contours given by Kerr and Westerhout[6]. Values of N_{H} and of the energy-dependent optical depth were calculated at each of nine points along the X-ray collimators. Given an assumed X-ray spectrum incident on the galactic hydrogen, we then computed the X-ray energy spectrum incident on the counter windows. This entire process was repeated at 0·5 s intervals throughout the flight, and the curves shown include the effects of superposed scans which were actually over slightly different parts of the sky.

The predicted rates are now even farther below those observed. Further, in the lowest energy channel the observed decrease with decreasing galactic latitude is much weaker than that predicted. On this point we agree with Bowyer, Field and Mack[1] that there is apparently too little interstellar absorption. In disagreement with these authors but in agreement with Henry *et al.*[2], we find that the apparent intensity of X-rays near 0·270 keV cannot easily be accounted for with a simple extrapolation of the high energy power law spectrum.

It is very unlikely that our soft X-ray measurements are significantly contaminated with a charged particle background. The background determined in flight was small (2·9 counts per second in the 0·15 to 0·48 keV channel, 1·8 counts per second in the 0·48 to 0·96 keV channel) and was the same for the 'Mylar' and 'Kimfol' counters. This background was evaluated from observations low in the atmosphere (80 km) while the rocket was on its way up; low in the atmosphere (80 km) while the rocket was on its way down; low in the atmosphere while the protective doors were still on; and throughout the flight when only the Earth was being viewed. All are in agreement within statistical uncertainties. There was no indication of an enhanced counting rate when the collimators passed through the plane perpendicular to the local terrestrial magnetic field.

The counting rate in the 0·15 keV to 0·48 keV channel of the 'Kimfol' counter divided by the corresponding rate of 'Mylar' counter was (after background subtractions) consistently 2·7 + 0·3. The measured ratio of the transmission of the two materials (flat, unstretched samples) at the carbon edge (0·284 keV) is 2·7 ± 0·2. The predicted ratio for most of our assumed spectra, which of course includes the effect of the larger energy window of the 'Kimfol', is near 5. A significant portion of this apparent discrepancy has its origin in the bulging of, particularly, the 'Mylar' film into the 3/16 inch slots of the film support frames. Laboratory attempts to evaluate this effect have proved unexpectedly difficult but result in lowering the predicted ratio to 3·6 ± 0·6.

From all these arguments we conclude that our counters respond primarily to soft X-rays. We cannot, however, exclude the possibility that some fraction of the response is due to soft X-rays of local (terrestrial or solar) origin. There was no evidence of enhanced response when the collimators crossed the ecliptic plane or the Earth's horizons at any point, including the region nearest the Sun. Nevertheless, we proceed to interpret our observations with three assumptions, one of which includes the possible existence of apparently isotropic soft X-rays of terrestrial or solar origin.

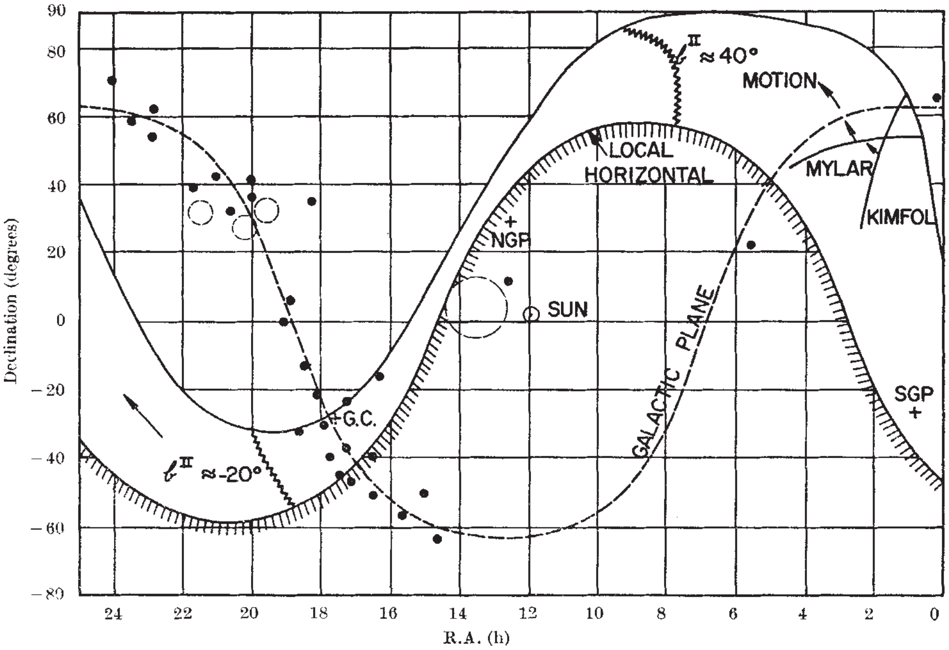

Fig. 2. Scan path in celestial coordinates. The black dots are the approximate positions of known X-ray sources. The broken circles indicate the regions of suspected enhanced soft X-ray emission. The large region near 14 h is discussed by Bowyer *et al.*[1]; the three small regions near 20 h are discussed by Henry *et al.*[2].

Three Assumptions for Interpretation

(*a*) The soft X-rays are all of extragalactic origin. This forces us to assume a soft X-ray source as well as the extrapolated $E^{-1\cdot5}$ spectrum. As is clear from Fig. 3, the problem of too little absorption with decreasing galactic latitude remains. This problem cannot be relieved by supposing less interstellar gas than is implied by the 21 cm measurement, or by supposing the helium to hydrogen relative abundance to be small, because the dependence on galactic latitude of the 0·45 to 0·96 keV channel agrees, approximately, with the predicted absorption. We have therefore been led to consider the effect of interstellar HI clouds. Let N_H be the average columnar hydrogen density in a given direction, and assume that the gas is clumped into randomly distributed clouds, each of columnar density N_c. Then the apparent X-ray optical depth is

$$\tau_e = \frac{N_H}{N_c}\left(1 - e^{-N_c\sigma}\right) \qquad (1)$$

where σ is the atomic X-ray absorption cross-section. If $N_c\sigma$ is much less than 1, τ_e is just σN_H. Otherwise τ_e is always less than σN_H. A choice of N_c near 12×10^{20} atoms cm^{-2} results in a tolerable fit to the galactic latitude dependence in the low energy channel and does not disturb the satisfactory fit of the 0·48 to 0·96 keV channel. The existence of some clouds as thick as 12×10^{20} atoms cm^{-2} has apparently been demonstrated by Heiles[7], but there is little direct evidence to support the idea that all interstellar hydrogen is structured in this way, in spite of Makova[8] and Grahl[9].

This analysis, requiring values of N_c near 10^{21} atoms cm^{-2}, may be inconsistent. Clouds of this thickness, particularly if the gas is cool, would themselves have optical depths of one or more at 21 cm. In this case cloud structure should be taken into account in deducing the values of N_H from the 21 cm emission surveys. We feel, however, that the entire subject of cloud structure is in too speculative a state for such refinement to be attempted here.

Finally, we consider the further soft X-ray flux needed to account for the large counting rate difference in the 0·15 to 0·45 keV channel and the smaller difference in the 0·48 to 0·96 keV channel. Obviously no definitive functional form can be determined. We choose arbitrarily a free–free spectrum of the form $E^{-1}\exp(-E/kT)$ and find that $kT = 0\cdot30$ keV fits satisfactorily. Values of kT as small as 0·15 keV or as large as 0·45 keV seem to be excluded. If therefore we assume all soft X-rays are of extragalactic origin, our data are consistent with an extragalactic intensity.

$$I = 11\,E^{-1\cdot5} + 100\,E^{-1}\exp(-E/0\cdot30)\ \text{photons}\ \text{cm}^{-2}\text{s}^{-1}\text{sterad}^{-1}\text{keV}^{-1}\ (E\ \text{in keV}) \qquad (2)$$

provided that all or at least a large portion of the interstellar gas is contained within clouds of $\sim 10^{21}$ H atoms cm^{-2} thickness.

(*b*) A background of solar or terrestrial soft X-rays. As one alternative we may assume that some undetermined solar or terrestrial source of soft X-rays contributes isotropically to our measured X-ray intensities but that the remainder are extragalactic. In this case, we regard the approximately 7 counts per second detected near $b^{II} = 0$ as a measure of the locally produced intensity and subtract it from all observations. The effect is to produce a steeper galactic latitude dependence of the data; but the dependence is still not in agreement with that pre-

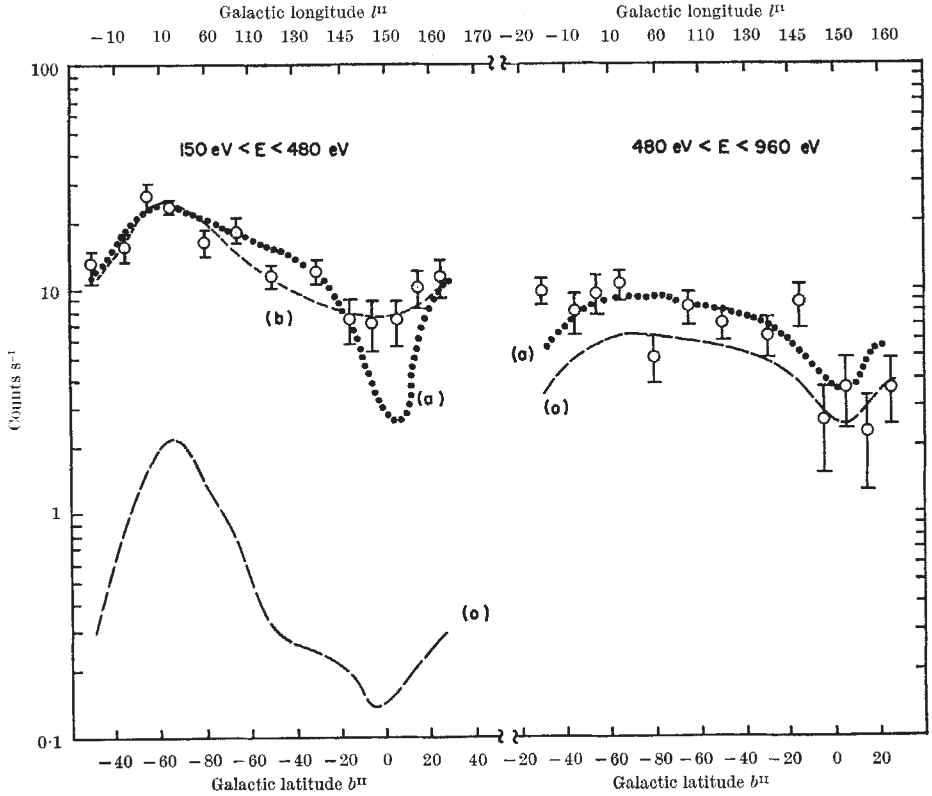

Fig. 3. Observed counting rate in the two low energy pulse height channels plotted against scan path in galactic latitude and galactic longitude. Only the downward-looking background has been subtracted. Dashed curves (○) are the predicted rates assuming normal interstellar absorption and an incident power law spectrum extrapolated from higher energy X-ray measurements. The dotted curves (*a*) assume an incident spectrum as given by equation (2) and interstellar absorption but with the gas distributed in clouds of 12×10^{20} atoms cm^{-2}. In case (*b*), it has been assumed that the soft X-rays detected near $b^{II} = 0$ are in fact isotropic and of solar or terrestrial origin. Curve (*b*) is the sum of an isotropic component (7 counts s^{-1}) and the predicted rate from an extragalactic intensity given by equation (2). Interstellar absorption is through gas distributed in clouds of 4×10^{20} atoms cm^{-2}.

dicted for cloudless interstellar absorption, and clouds of $N_c \approx 4 \times 10^{20}$ atoms cm^{-2} are required. Again our data imply a further extragalactic soft X-ray component. Somewhat accidentally, this additional component turns out to be the same as that required under (*a*) above. The subtracted background is just compensated by the larger effective interstellar absorption which results from distributing the hydrogen in thinner clouds.

(*c*) An apparent background from unresolved population II objects. As a final alternative, we consider the possibility that the excess soft X-ray intensity unexplained by the extrapolated power law spectrum arises from unresolved population II objects, possibly convective stars with coronas emitting X-rays. Because such objects are, on the average, farther from the galactic plane than the gas is, a weak dependence on galactic latitude is to be expected. To investigate this possibility we have computed a number of integrals of the form

$$I = S_0 \int_0^\infty \exp - \left(\frac{r}{z_s \sin b}\right)^{z} e^{-\tau}\, dr \qquad (3)$$

where

$$\tau = \sigma n_0 \int_0^r \exp - \left(\frac{r'}{z_s \sin b}\right)^2 dr'$$

z_g characterizes the height dependence of the gas distribution above the galactic plane, z_s characterizes the height dependence of whatever may be emitting the soft X-rays, σ is the energy dependent absorption cross-section[5] and n_0 is the number density of gas atoms in the galactic plane. Acceptable fits to the latitude dependence of our observations in the lowest energy channel can be obtained with $n_0 = 1$ cm^{-3}, $z_g = 94$ pc (160 pc between half-density points) and $z_s = 400$ pc. The gas distribution we are forced to assume is significantly narrower than that deduced by Schmidt[10], whose value for the distance between half-density points was 220 pc, although Kerr and Westerhout[6] state that observations with the Australian 210 foot paraboloid (1/4° beam) indicate a lower value near 160 pc. If we allow the spectrum of these hypothetical soft X-ray sources to spill over into our 0·48 to 0·96 keV channel in an attempt to account for the extra intensity needed there, we find a large unexpected bump near $b = 6°$ which we do not observe. The model is highly idealized, of course, particularly because distances of the order of only a hundred parsecs are involved, and the bump is the result of delicately competing effects of the two assumed Gaussian distributors.

The required source strength (s_0) is about 4×10^{-19} photons cm^{-3}s^{-1}sterad^{-1}keV^{-1} at 0·26 keV. Expressed in terms of the luminosity of the Sun (quiet Sun at solar maximum) at 0·26 keV, this source strength implies 13 equivalent Suns per pc^3. Alternatively, if only F and G stars contribute, their soft X-ray luminosity would have to average some 1,500 times that of the Sun.

The maximum soft X-ray intensity we observe is in the direction $b^{\rm II} = -60°$, $l^{\rm II} = 10°$, and has the value

$$I = 195 \pm 20 \text{ photons cm}^{-2}\text{s}^{-1}\text{sterad}^{-1}\text{keV}^{-1} \text{ or}$$

$$J = (3{\cdot}4 \pm 0{\cdot}4) \times 10^{-25} \text{ ergs cm}^{-2}\text{s}^{-1}\text{sterad}^{-1}\text{Hz}^{-1}$$

at ~ 0·26 keV, and is

$$I = 20 \pm 3 \text{ photons cm}^{-2}\text{s}^{-1}\text{sterad}^{-1}\text{keV}^{-1}$$

$$J = (3{\cdot}4 \pm 0{\cdot}5) \times 10^{-25} \text{ ergs cm}^{-2}\text{s}^{-1}\text{sterad}^{-1}\text{Hz}^{-1}$$

at 0·9 keV. These values are weakly dependent on the assumed energy spectrum of incident X-rays. The corresponding values near the galactic plane ($l^{\rm II} \approx 155°$) are

$$I = 57 \pm 8 \text{ photons cm}^{-2}\text{s}^{-1}\text{sterad}^{-1}\text{keV}^{-1}$$

at 0·26 keV and

$$I = 6 \pm 1{\cdot}5 \text{ photons cm}^{-2}\text{s}^{-1}\text{sterad}^{-1}\text{keV}^{-1}$$

at 0·9 keV. The quoted uncertainties include counting statistics and estimated systematic errors such as uncertainties in window thickness or background subtraction.

If we ignore for the moment the distinct possibility that galactic objects contribute to the soft X-rays observed, our data imply an extragalactic component with an intensity given by expression (2). It should be emphasized that we have by no means established the analytic form of this expression. The first term is merely the power law spectrum extrapolated to low energies, the second term a convenient computational device. As pointed out before, expression (2) is appropriate whether or not the residual intensity near $b^{\rm II} = 0$ is regarded as a locally produced background, provided that the apparently anomalous variation of the soft X-ray intensity with $b^{\rm II}$ is attributed to structure in the HI distribution (clouds).

The second term of expression (2) when evaluated at 0·280 keV and 0·900 keV gives 140 and 5·5 photons cm^{-2}s^{-1}sterad^{-1}keV^{-1} or equivalently $2{\cdot}6 \times 10^{-25}$ and $3{\cdot}3 \times 10^{-26}$ ergs cm^{-2}s^{-1}sterad^{-1}Hz^{-1} respectively. If interpreted as free–free radiation from a hot intergalactic plasma, these two values for the soft X-ray intensity are consistent with a temperature of about 3×10^6 K for the steady state model (density = $1{\cdot}1 \times 10^{-5}$ cm^{-3}) discussed by Field and Henry[11]. The measured values do not match the intensities predicted for any of the evolving models discussed by these authors. For example, a fair fit can be obtained to their model with $T = 10^6$ K, $q_0 = 1/2$, $w = 0{\cdot}1$, but only if the predicted intensity is reduced by a factor of about 30. A decrease in the adopted density ($2{\cdot}2 \times 10^{-5}\, q_0$ cm^{-3}) by $\sqrt{30}$ would, of course, reduce the intensity by the required amount. But if the cosmological density, q_0, T and w (related to the required red-shift cut-off) are all regarded as free parameters, it is difficult to see how an intergalactic hot plasma could be involved. Our conclusions here differ from those of Henry *et al.*[2] and Bowyer, Field and Mack[1] because we have measurements in two different soft X-ray energy regions. This provides some spectral information on the supposed extragalactic radiation and so permits an independent (but cosmology dependent) estimate of the temperature. The other workers assumed cosmological densities, and so were forced to attribute the radiation to a lower temperature plasma. The higher temperature assignment is in itself sufficient to reduce the level of predicted intergalactic ultraviolet radiation below 10^{-23} erg cm^{-2}s^{-1}sterad^{-1}Hz^{-1}. R. A. Sunyaev (personal communication) concludes that this is the critical level above which neutral hydrogen in the peripheries of galaxies should not exist.

It is difficult, in view of the meagre observational material that is available, to assess the plausibility of our suggestion that an appreciable fraction of the observed soft X-ray intensity has its origin in unresolved population II objects; but it is easy to show that if a total of N discrete sources of uniform luminosity are distributed at random within a sphere of radius R (R in our case corresponds to unit optical depth), the total number of observable discrete sources brighter than F is

$$n\,(>F) = \frac{1}{\sqrt{N}} \left(\frac{4\pi I}{3\,F}\right)^{3/2}$$

where I is the apparent diffuse intensity from unresolved discrete sources. Henry *et al.*[2] report one apparent soft X-ray source at a 3σ level; Bowyer, Field and Mack[1] report none. From our own survey, which covered about 1/12 of the sky, we estimate that any characteristically soft X-ray discrete source with a flux greater than 1·3 photons cm^{-2}s^{-1}keV^{-1} would have been noticed. The portion of the diffuse intensity we are attempting to explain amounts to about 60 photons cm^{-2}s^{-1}sterad^{-1}keV^{-1} (the value in the galactic plane) and so a rough estimate of the number of contributing sources (with $n = 12$) is $N = 5 \times 10^4$, or 10^{-2} (pc)$^{-3}$. These estimates can vary greatly as the results of new surveys with higher sensitivity become available.

For the present, because the required source number density is smaller than the density of known objects, we feel that this suggested soft X-ray origin cannot be ruled out.

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Early Pre-Cambrian Onverwacht Microstructures: Possibly the Oldest Fossils on Earth?

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The microstructures show some resemblance to very simple organisms, but their morphology is poor and their size range is very great.

THE presence of "cup-shaped" and spherical microstructures in the early Pre-Cambrian ($>3\times10^9$ yr old) sedimentary rocks of the Onverwacht Series of South Africa was first described in 1967 (unpublished report by B. N., L. A. N., C. G. Engel, A. E. J. Engel, G. O. W. Kremp and C. M. Drew), and then in 1968 (refs. 1 and 2). Later additional information was presented on these "organized elements" and also on the geology of the Onverwacht Series. (The term "organized element" was first proposed[4] in order to designate microstructures of unknown origin in carbonaceous meteorites. Both the crystal lattices of minerals and the structures of fossils are organized and the term "element" means entity.) Following these initial reports, further studies in our laboratory led to additional and detailed information regarding the Onverwacht microstructures. These new data emphasize the fact that, contrary to popular opinion, these particles cannot definitely be called microfossils on the basis of currently available information.

The argillaceous cherts and carbonates in the Onverwacht constitute, at present, the oldest known sedimentary rocks on Earth. The Onverwacht is part of the Swaziland System which is well exposed in the Barberton–Badplaas region of the Eastern Transvaal, South Africa. The Swaziland System consists of three rock series: the youngest is the Moodies Series; the median is the Fig Tree Series and the oldest member is the Onverwacht Series. The oldest sedimentary rocks in the Onverwacht, containing microstructures, lie approximately 35,000 feet stratigraphically below the younger Fig Tree sediments, from which similar microstructures have been described in the past few years as fossil algae and flagellates[5,6].

The Onverwacht rocks are $>3\times10^9$ yr old, and consist chiefly of volcanic rocks such as pillow lavas, laid down in water, and of subordinate quantities of sedimentary rocks and tuffs. Geological evidence—cross-bedding, laminations, and so on—indicates that the sediments were also deposited in water. Most of the Onverwacht is metamorphosed, but it has been reported that some of the sediments were not affected by severe thermal metamorphism (personal communication from A. E. J. Engel). Yet it is possible that the degree of metamorphism of these sediments is higher than estimated. Recent studies by local investigators seem to indicate that the apparently non-metamorphosed appearance of the Onverwacht sedimentary rocks may be deceptive (D. A. Pretorius, personal communication). A more detailed description of the geology of the Onverwacht is given in refs. 3, 7 and 8.

The Onverwacht Microstructures

Microstructures were studied both in petrographic thin sections and in powdered preparations from eleven sedimentary zones along the Onverwacht stratigraphic column. The rock samples included the oldest known sediments on Earth as well as younger ones from throughout the Onverwacht.

The microstructures do not seem to be uniformly distributed in the rock samples; they appear in small "pockets". Often great patience is necessary to locate them on slides and in thin sections and/or to find sufficient numbers of them for meaningful studies of size distributions. The petrographic thin sections and the powdered preparations both revealed the same microstructures. This indicates that those in powdered preparations are indigenous particles and not recent contaminations. We exercised great care in making the powdered preparations. The surfaces of each rock sample were first drilled off with a portable drill, then ultrasonically cleaned. Samples were ground in acid-cleaned mortars in a room ventilated by filtered air. The powdered rock was gravity separated in triple distilled water and a slow-settling fraction was mounted on microscope slides with Canada balsam. Some powdered rock samples were treated for 2 h with boiling 6 N HCl; this was followed by treatment for 2 h with boiling 48 per cent HF. Another rock sample was first extracted in a Soxhlet apparatus with benzene and methanol and then suspended in 4 per cent aqueous KOH and treated with $\sim 2\cdot8$ per cent ozone in a stream of oxygen for 18 h, followed by treatment in 10 per cent KOH with 30 per cent H_2O_2. The microstructures seemed to be unaffected by these chemical treatments and were, in fact, indistinguishable from those particles found in untreated samples. The resistance of the microstructures to these chemicals provides indirect evidence of their