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On the Stellar Origin of Low Energy Cosmic Rays [and Discussion]

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On the stellar origin of low energy cosmic rays

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The large solar flares associated with cosmic-ray events release total bolometric energies in the region 10^{24}–10^{25} J. This is of the order 10^{-5}–10^{-6} of the normal bolometric energy emission of the Sun. The condition of the M and K type stars when they flare is entirely different; the rate of energy release during the flare is of the same order as the normal energy release of the star in the quiescent condition. Although these dwarf stars are in a markedly different evolutionary condition compared with the Sun recent simultaneous radio and optical observations of the flares have given decisive indications that the physical processes, involving magnetic field collapse of several hundredths of a tesla, must be similar to the flare mechanism in the Sun. Adopting the factor, which has been determined empirically in the case of the Sun, for the conversion of flare energy to cosmic-ray energy, estimates are made of the fraction of galactic cosmic rays which may be generated in the flares on the M and K type stars. It is shown that these stars may be the major source of the galactic cosmic rays for energies from 10^6–3×10^8 eV and that the K type stars may contribute one fifth of the total cosmic-ray energy up to 10^9 eV.

1. Introduction

Recent observations of the flare phenomena on the M type red dwarf stars have given evidence which indicates that the phenomena are fundamentally similar to the flares on the Sun. Large solar flares are associated with the production of low energy cosmic rays, and given the identity of the flare mechanism on the M type stars it seems reasonable to assume that these stars will also produce cosmic rays during the flare phase. The purpose of this paper is to make estimates of the probable contribution of the M type and K type stars to the total cosmic-ray flux in the Galaxy.

In October 1948 Luyten (1949) discovered the binary star L 726-8AB (UV Ceti) and on 7 December 1948 he observed a variation of 2 magnitudes in the brightness of this star. Soon it became evident that earlier observations of increases in brightness of the stars WX Ursae Majoris and Ross 882 by van Maanen (1940) were similar occurrences. In 1950 the International Astronomical Union recognized the UV Ceti class as a new type of variable star. They are M type red dwarfs and, because of their low temperatures (less than 3000 K) and luminosities, are observable only in the solar neighbourhood. They are characterized by sudden but irregular increases in brightness. Increases of up to one half magnitude may occur every few hours, and there are occasional observations of increases to 6 magnitudes. The flares are typified by a rapid increase to maximum which takes place within a few seconds, and a much slower decay. For the smaller flares the star may return to its quiescent condition in about 30 min; although in some cases several hours have elapsed before the normal state is restored.

The physical condition of these red dwarf stars is a matter of considerable interest. The type star UV Ceti, for example, is a binary of absolute magnitude 16 with component masses each about 0.04 $M_{\odot}$, luminosities 10^{-5} $L_{\odot}$, and radius 0.088 $R_{\odot}$. Of the red dwarf flare stars commonly observed YZ CMi (Ross 882) is typical of the higher mass range with absolute magnitude

12.3, mass 0.30 $M_{\odot}$ and radius 0.25 $R_{\odot}$. Although a considerable number of the red dwarf stars so far studied are binaries it seems unlikely that this has any connexion with their flaring properties since the typical separation of the components is about 1000 stellar radii. Hayashi's (1961) work on the evolutionary tracks of condensing stars indicates that a star of mass 0.4 $M_{\odot}$ or less will reach the main sequence as a wholly convective structure without any intervening stage of radiative equilibrium. The red dwarf stars lie in this category. It seems that the central mass and temperature do not reach the stage where hydrogen burning can occur. As contraction continues, the star ultimately reaches the stage of complete degeneracy and becomes a black dwarf without passing through the normal stages of stellar evolution. Depending on the mass, the time scales for the life of these stars before they reach the black dwarf stage are of the order 10^7–10^8 years. These time scales are small compared with the age of the Galaxy and hence the number of stars which have evolved to the black dwarf stage may be very large.

During the contracting phase the energy release per unit area remains nearly constant and since the radius is decreasing rapidly the angular momentum must be lost over a short time scale. In a qualitative sense these conditions may be expected to produce strong magneto-hydrodynamic effects and – by comparison with the Sun – pronounced flare phenomena. Although the violence of the flare phenomena has been understood since the observations of Luyten it is only recently that combined radio and optical observations of the flare stars have led to the conclusion that the red dwarf flare phenomena are fundamentally similar to the solar flare events and hence that these stars must be considered as possible sources of cosmic-ray particles.

The discovery that the K type stars also exhibit flare phenomena is more recent. In 1953 while studying the H_{α} emission from stars in the Orion nebula Haro (1953) found resemblances to flare type stars. A number of workers subsequently confirmed that the K type stars in Orion and in other stellar aggregates were, indeed, exhibiting flare properties similar to that of the M type dwarfs. These were originally known as 'flash stars' or 'nebular variables' to distinguish them from the classical red dwarf flare stars of type M, but it is now thought that the diversities are due to different stages of evolution and that physically, the phenomena are similar to the M type flares. The investigations of the flares on K type stars have been made especially by Haro, Rosino & Ambartsumian and their co-workers (Haro 1968). They have observed many thousands of these objects principally in the Orion aggregate, in the Pleiades, in the Coma Berenices cluster, in Praesepe and the Hyades. In 1968 Haro listed several hundred of the K type flare stars, and in 1970 from the observations of the Pleiades at Burakan, Ambartsumian *et al.* (1970) and Ambartsumian (1970) concluded that all the members of the Pleiades aggregate brighter than visual magnitude 13.3 were flare stars, and that, in Orion, one quarter of all RW Aurigae variables were flare stars. His latest estimate is that 1000 of the stars in the Pleiades aggregate are observable flare stars (Ambartsumian *et al.* 1972, 1973). Evidence will be given that the simultaneous radio and optical observations of these K stars show the similarity of the phenomenon to the flares on the M type stars and hence the K stars must also be considered as possible sources of cosmic-ray particles.

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2. Comparison of the energies in the stellar flares and the solar flares

When Luyten observed the 2^m flare on UV Ceti in 1948 he estimated that the total energy in the flare was 4×10^{24} J. A similar total energy of 5×10^{24} J was calculated by Liller (1952) for the flare which he observed photoelectrically on the star BD + 20° 2465. These surprisingly high values for the flare energies on the red dwarf stars subsequently received adequate confirmation. In the statistics on 166 flares measured photoelectrically in the blue region at the Crimean Astrophysical Observatory, covering the stars UV Ceti, YZ CMi, AD Leo, and EV Lac, Gershberg & Chugainov (1968) found that the peaks of the histograms were at $3 \times 10^{24 \pm 2}$ J and that more than half the flares radiated $10^{24 \pm 1}$ J. Table 1 gives the rate of energy emission in the quiescent state by these stars in the B colour over a bandpass of 97 nm compared with the total flare energy output in B colour at the peak of the histogram in the work of Gershberg & Chugainov (1968).

Table 1. Quiescent and flare energies in M type dwarfs

	rate of energy release in quiescent state in B colour/J s^{-1}	total energy in B colour in each flare at maximum of histogram/J
UV Ceti	1.86×10^{21}	2×10^{23}
YZ CMi	2.32×10^{22}	10^{24}
EV Lac	5.94×10^{22}	10^{25}
AD Leo	8.20×10^{22}	5×10^{24}

Thus in the normal flare occurrences on the red dwarf stars there is an eruption of energy equivalent to the energy release of the star in its quiescent state for minutes. In some individual cases of large flares this situation may continue for hours. For example, in the case of the flare on YZ CMi, observed on 19 January 1969, Kunkel (1969) found that the flare eruption released energy equivalent to the normal quiescent output for 10^4 s.

Since the largest solar flares are difficult to see in white light against the photospheric continuum it is evident that there must be orders of magnitude difference between the ratio of flare energy to normal photospheric emittance for the flare stars and the Sun. The quantitative comparison of these energies is important for the discussion in this paper. There is no satisfactory theory from which to calculate the fraction of the solar flare energy which is manifested as cosmic-ray energy and in § 5 the empirical factor, established observationally in the case of solar flares, will be applied to the flare stars. Unfortunately the available measurements of the flare energies are largely in narrow band U.B.V. for the flare stars whereas for the Sun, the flare energies are measured bolometrically. The bolometric measurements for the Sun are given in table 2 for flares of importance 1, 2 and 3 (Allen 1973).

Comparison of tables 1 and 2 shows that the energies of the stellar flares as measured in B colour are of the same order as the bolometric energy of the largest solar flares. In order that the appropriate comparison with the Sun can be made it is necessary to make an estimate of the probable bolometric energy in the stellar flares. In § 5 the systematic flare star measurements of Moffett (1973) will be used as the basis for the cosmic-ray energy estimates. His measurements were in the U.B.V. with the filters and bandwidths given in table 3. Moffett's measurements on the M type stars in the quiescent condition establish the relation between the U.B.V. and bolometric energy output. For example in the case of UV Ceti the bolometric luminosity is 10^{23} J s^{-1}, whereas the U.B.V. value measured by Moffett with the filters in table 3 is 6.98×10^{21} J s^{-1} – that is a ratio of 14.3 from U.B.V. to bolometric. There is no decisive means of making a similar comparison for the flare condition because, the effective flare temperatures are of the order of 10 000–20 000 K compared with the quiescent temperature of not more than 3000 K. All available spectroscopic data on the flares show the sharp rise of intensity of the flare light in the ultraviolet region and the correction from U.B.V. to bolometric must be considerably in excess of the situation which applies in the quiescent condition. Kunkel (1970) has made the most detailed study of the problem and his conclusion is that the optical energies of the flares as determined by the narrow range of wavelengths in the U.B.V. filters must be increased by factors of between 80 and 200, for comparison with the bolometric solar flare energies. In §5 we adopt the factor as 100 as between the stellar flare energies measured in U.B.V. with the table 3 filters and their bolometric value. In the case of UV Ceti for example, this means that, on the basis of Kunkel's studies we adopt a value seven times greater than the factor of 14.3 which would apply on the basis of the actual measurements of the star in the quiescent state, whereas the limits assigned by Kunkel would suggest a value lying between 5.5 and 14 times greater than the quiescent factor.

Table 2. Quiescent and flare energies for the Sun

rate of energy release in quiescent state (bolometric)/J s^{-1}	total energy in flare (bolometric)/J
3.82×10^{26}	importance 1 – 1.9×10^{22}
	importance 2 – 2.5×10^{23}
	importance 3 – 1.6×10^{24}

Table 3. U.B.V. filters used in M type flare measurements

filter	λ/nm	$\Delta\lambda$/nm
V	555	85
B	435	97
U	350	70

3. Radio observations of the stellar flares – evidence for the solar flare type emission mechanism

Although the rate of energy emission in the M type stars is only of the order 10^{-4} that of the Sun in the quiescent state, the measurements and discussion in §2 show that for the stars listed in table 1 the flare energies will be of the order 10^3 times greater than the energy of the solar flares of importance 3 with which cosmic-ray emission is associated. In principle, therefore, the red dwarf stars might be sources of cosmic-ray particles similar to the Sun. However, the M type stars and the Sun are so radically different in their evolutionary state that such comparisons need interpreting with caution unless evidence is available that the mechanism of flare production in the star is similar to that in the Sun. Since the discovery of the red dwarf flares there have been many theories advanced to account for the phenomena, extending from the accretion theory of Greenstein (1950) to the suggestion of Ambartsumian (1954) that the flares resulted from a nuclear energy release deep inside the star. A survey will be found in the work by Gershberg (1971). Here it is necessary only to discuss the recent research which appears to be decisively in favour of a solar flare type mechanism.

The suggestion that star spots existed on the red dwarfs analogous to sun spots has received support from a number of authors since the original suggestion of Kron (1952). A recent discussion of the spot model has been given by Bopp & Evans (1973). The association of solar flares with sun spot groups is well known and there has been increasing circumstantial evidence for the similarity of the stellar and solar flares. For example, the somewhat meagre spectroscopic data on the red dwarf flares show many similarities to the solar flares – that is Balmer series in emission, emission lines of He I, He II, Ca II, H and K; and also the asymmetry in the line profiles. Unfortunately, there has been no conclusive evidence for the detailed mechanism of the star flare production, especially with regard to the critical question of the involvement of magnetic fields in the phenomenon. In this respect it appears that recent observations of the radio emission from the red dwarf flares have a significant bearing.

The attempts to detect radio emission associated with the flares on the red dwarf stars commenced at Jodrell Bank in 1958 and in Australia in 1960. A recent summary of this work has been given by Lovell (1971). For some time the radio results were only sufficient to define a close temporal relation between the maximum phases of the optical flare and radio emission. Although it seemed that the radio emission always tended to lag behind the peak optical emission, decisive evidence was not available until 1969. On 19 January 1969 successful correlated radio and optical observations of a large and long duration flare on YZ CMi (Ross 882) were obtained by Lovell at Jodrell Bank, (radio) (Lovell 1969), by Andrews at Armagh (visual) and by Kunkel at Cerro Tololo (photometric) (Kunkel 1969). The delay of many minutes between the optical flare maximum and the radio emission was evident, and Kahn (1969) interpreted this in terms of a shock wave moving out from the photosphere with a speed of Mach 2, exciting the radio emission at a height of about 10^{10} cm in the stellar atmosphere at the plasma frequency appropriate to the observing frequencies of 240 and 408 MHz.

An even more decisive event was observed on 11 October 1972 when at 21h 18min 52s U.T., Mavridis and Contadakis in Thessaloniki obtained photoelectric records of a particularly large flare on UV Ceti (the pen was off scale at 4.55 mag. in B colour). The sharp front of the flare was paralleled 8 min later in the 408 MHz record observed at Jodrell Bank (Lovell, Mavridis & Contadakis 1974). In his theoretical treatment of this observation Kahn (1974) has been able to obtain a more definitive model for the flare event. He estimates the magnetic field at the surface of the star to be 9×10^{-2} T. On the basis of the conventional model for the solar flare he assumes that the energy is released during the reconnexion of the lines of force in the magnetic field and that the bubble of plasma then expands into the stellar corona behind the shock wave. At a height of 1.4×10^{10} cm the 408 MHz radiation can be released, at which point the magnetized bubble has expanded by 5–6 times in linear dimensions and the magnetic field has dropped to 2×10^{-3} T. He computes that the 408 MHz radiation is by synchrotron emission from 6.4×10^{36} electrons and that the magnetic energy in the bubble of 5.4×10^{24} J remains larger than the particle energy. Hence the acceleration process is still feeding energy into the electrons. The predicted rate of mass loss into the stellar wind is 3.4×10^{14} g s^{-1} or about 10^{-11} $M_{\odot}$ per year. This rate of mass loss per star, although significant for the interstellar medium, cannot seriously effect the evolutionary life time of the star.

There has not yet been any similar detailed investigation of the flares on the K type stars. However, the similarity to the M stars has been substantially confirmed by the simultaneous radio and optical observations of the flares made in Australia (Slee, Higgins, Roslund & Lyngå 1969; Slee & Higgins 1971). The powers emitted are greater by 10^3 compared with the M type dwarfs, but the ratio of the optical flare energy to that in the radio spectrum is the same as for the M dwarfs. This ratio of radio to bolometric is 10^{-5}, the same as that for the large solar flares. Earlier conclusions by Lovell (1964) that the ratio for the stars differed from that for the solar flares were based on an erroneous comparison using U.B.V. energies for the stellar flares but bolometric energies for the solar flares as pointed out by Kunkel (1970). This remarkable similarity of the ratio of energies emitted in the flares over six orders of magnitude in wavelength and over stellar types from M to G is a further substantial indication that the same flare mechanism is active in each case.

4. Cosmic rays from stellar flares

From the evidence given in §3 there now seem to be compelling reasons for believing that the solar flares and the stellar flares are produced by similar processes. The theoretical treatment by Kahn summarized in §3 for the flares on the M type dwarfs is based on the Parker (1955, 1957) model for the solar flares in which magnetic fields of several hundredths of a tesla at the point of initiation of the optical flare are involved. Since the existence of the magnetic field and the changes which occur during the flare process are cardinal features of the argument advanced in this paper it is important to draw attention to the work of Bopp & Evans (1973). These authors have made a photometric study of the flare stars BY Dra and CC Eri *outside* the periods of flare activity. They obtain excellent agreement with the observed photometric light curves on the interpretation that the variations arise from the rotation of the star with cool, dark spots on the surface. They estimate that the magnetic field necessary to store the energy dammed back by the spots is in the range of a few tenths of a tesla and that the flare phenomena is initiated by the magnetic field collapse.

Further support for the view that the star and solar flare phenomena are similar physical manifestations is the observational and theoretical evidence (Lovell 1969; Kahn 1969, 1974) that the coronal temperature where the radio flares occur on the star is of the order 10^6 K – the same as in the case of radio flares in the solar corona.

Although no agreement exists as to the processes by which cosmic rays are produced when large solar flares occur, the observational evidence is clear that a fraction of the flare energy is, in fact, emitted as cosmic rays in the energy range up to 10^8–10^9 eV. Since, in the stellar flares, the evidence now seems conclusive that the magnetic fields essential for the radio emission are present as in the Sun, and that the emission processes are similar, we proceed on the assumption that cosmic rays will be emitted in the stellar case as in the solar case. In §5 we calculate the appropriate energy release in the Galaxy and in §6 these estimates are compared with the total cosmic-ray energy in the Galaxy in different energy ranges.

5. The total flare energy output from the stars

The cosmic-ray flux contributed by the stellar flares may be expressed as

$$F = \int \phi(M) E(M) \rho \beta \chi \, \mathrm{d}M \ \mathrm{J\ s^{-1}\ pc^{-3}}, \tag{1}$$

where $\phi(M)$ is the luminosity function of the stars; (i.e., the number per pc^3 in the absolute magnitude range $M_{\mathrm{V}}^{\pm}\frac{1}{2}$); $E(M)$, the mean bolometric energy output per flare for stars in the absolute magnitude range $M_{\mathrm{V}}^{\pm\frac{1}{2}}$; χ, the fraction of class $\phi(M)$ exhibiting the flare phenomena; β, the fraction of time for which the stars emit E; and ρ, the conversion factor for bolometric flare energy to cosmic-ray energy. The following comments may be made about these various factors.

(a) *The luminosity function $\phi(M)$ and the fraction χ*

Since the M type dwarfs are of low luminosity the population counts are known only for the solar neighbourhood. The data given by van Rhijn (1946) show that for absolute visual magnitudes in the range M_{V} 10 to M_{V} 15 the luminosity function is 0.068. However, the most recent investigations by Weistrop (1972) show that the red dwarfs are, in fact, 5 to 10 times more numerous. The appropriate values of $\phi(M)$ taken from table VIII and figure 12 of Weistrop's paper are given in table 4. Weistrop terminates the function at $M_{\mathrm{V}} = 15$, corresponding to masses of 0.08 $M_{\odot}$ but he refers to the existence of stars of smaller masses and to the possibility that a significant amount of mass exists in stars fainter than $M_{\mathrm{V}} = 15.5$. Since the flare energy data on the M dwarfs extends to stars with $M_{\mathrm{V}} = 16.55$, the Weistrop function has been extrapolated to $M_{\mathrm{V}} = 16$, to give the relevant value of ϕ(M) in the last line of table 4.

Table 4. Luminosity functions for red dwarf stars

$M_{\mathrm{V}}^{\pm\frac{1}{2}}$	$\phi(M)$
10	0.01
11	0.03
12	0.06
13	0.13
14	0.25
15	0.40
16	0.60

The fraction χ of these stars exhibiting the flare phenomena is again known only for the solar neighbourhood. In an investigation of about 1000 flares in the U-band, Kunkel (1973) concludes that the small number of known flare stars in the solar vicinity is due to low flare visibility and is therefore a selection effect and is not a result of differences in the M dwarfs as a group. On this basis we take χ as unity.

For the K type stars we take the values of $\phi(M)$ based on the statistics of van Rhijn (1946) and Allen (1973) as given in table 5. The only guidance available regarding the value of χ for the K stars is the conclusion of Ambartsumian *et al.* (1972) that in the Pleiades all stars brighter than $M_{\mathrm{V}} = 13.3$ flare, but that no flares have been observed in K stars fainter than $M_{\mathrm{V}} = 13.3$. In table 5 $\phi(M)$ has therefore been terminated at $M_{\mathrm{V}} = 13$.

Table 5. Luminosity functions for K type stars

$M_{\mathrm{V}}^{\pm\frac{1}{2}}$	$\phi(M)$
6	15×10^{-4}
7	30×10^{-4}
8	25×10^{-4}
9	15×10^{-4}
10	4×10^{-4}
11	2×10^{-4}
12	1×10^{-4}
13	4×10^{-4}

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(b) *The flare energy E and time factor β*

Examples of the values for the flare energy in the M type dwarfs have been given in §2 and table 1. However, we require the rate of output of flare energy, and in order to obtain this from the data quoted in §2 assumptions have to be made about the rate of occurrence of flares of various magnitudes. This information is available, but fortunately a far more detailed investigation by Moffett (1973) has recently given the value of the product $E\beta$ more precisely. Moffett used a high speed photometric recording instrument at the McDonald Observatory and studied 414 flares in 470 h of monitoring on 7 flare stars with separate U.B.V. filters. For this work he was able to evaluate the total energy radiated per day by the flare activity as given in table 6.

Table 6. U.B.V. flare energies for 7 M type dwarf stars

star	M_v	energy per day in U.B.V./J
YY Gem	8.36	3.1×10^{26}
AD Leo	10.98	2.3×10^{25}
EV Lac	11.50	1.1×10^{26}
EQ Peg	11.33	1.4×10^{26}
YZ CMi	12.29	6.6×10^{25}
UV Ceti	14.78	1.1×10^{25}
CN Leo	16.55	4.6×10^{24}

The evidence from Moffett's observations and also from the work of Kunkel (1973) is that E is a weak function of M_v. The relationship is not yet well determined. We have therefore evaluated the integral in (1) by taking mean values from table 6 which correspond approximately with the M_v values of table 4 to give the $\phi(M)E(M)\beta\chi$ products in table 7. Summation of the last column in table 7 gives a value for

$$\Sigma\phi(M)E(M)\beta\chi = 2.31 \times 10^{25}\,\text{J d}^{-1}\,\text{pc}^{-3}.$$

Table 7. Red dwarf U.B.V. flare energies as function of magnitude

$M_v^{\pm\frac{1}{2}}$	energy per day in U.B.V. derived from table 6/J	$\phi(M)E(M)\beta\chi$/J d^{-1} pc^{-3}
10	1.6×10^{26}	1.6×10^{24}
11	9.1×10^{25}	2.7×10^{24}
12	6.6×10^{25}	3.9×10^{24}
13	3.8×10^{25}	5.0×10^{24}
14	1.1×10^{25}	2.8×10^{24}
15	1.1×10^{25}	4.4×10^{24}
16	4.6×10^{24}	2.7×10^{24}

These measurements refer to a part only of the stellar surface. There is no evidence on which to judge the directivity effect of the flares but clearly, at least a factor of 2 must be involved. Using this factor, and the conversion factor of 10^2 from U.B.V. to bolometric deduced in §2 we arrive at a bolometric value for the M type stars.

$$\Sigma\phi(M)E(M)\beta\chi = 4.62 \times 10^{27}\,\text{J d}^{-1}\,\text{pc}^{-3}$$
$$= 5.8 \times 10^{22}\,\text{J s}^{-1}\,\text{pc}^{-3}.$$

For the K stars there are no similar statistics to those presented above. Based on the identity of the phenomenon between the K and M flares discussed in §3 we make the assumption that the observed increase of 10^3 in the flare energy for K stars compared with the M stars applies throughout the magnitude range over which flares are observed, that is brighter than $M_v = 13.3$. No information is available about the dependence of $E(M)$ on M_v. Since in the M type stars $E(M)$ depends only weakly on M_v, we take the mean value of $E\beta$ from table 6 increased by the factor of 10^3 for the observed greater energy in the K stars compared with the M stars, and assuming the same correction to bolometric energies we obtain for $E(M)\beta$ the bolometric value of 9.5×10^{30} J d^{-1}. On the basis of Ambartsumian's results referred to in §4 (*a*) we take $\chi = 0$ for stars fainter than $M_v = 13.3$ and $\chi = 1$ for stars of greater magnitude. Summation of $\phi(M)$ in table 5 then gives

$$\Sigma\phi(M)\chi = 9.6\times10^{-3}.$$

Introducing the directivity factor of 2 gives the bolometric value for the K type stars:

$$\Sigma\phi(M)E(M)\beta\chi = 1.82\times10^{29}\,\mathrm{J\,d^{-1}\,pc^{-3}} = 2.1\times10^{24}\,\mathrm{J\,s^{-1}\,pc^{-3}}.$$

(*c*) *The conversion factor* ρ

A number of authorities agree that the total energy of the cosmic ray events associated with the major solar flares producing them is of the order 10^{23} J, where the bolometric flare energy is 10^{25} J (see for example Fichtel & McDonald (1967), Kiepenheuer (1965)). Since there are not yet any agreed methods of calculating the processes of conversion of the flare energies in the Sun to cosmic-ray energies we take this empirical factor of 10^{-2} for the value of ρ and make the assumption that it applies similarly to the processes of conversion of the energy in the flares on the M type and K type stars to cosmic rays.

(*d*) *The cosmic-ray flux from the M and K stars*

Insertion of these various parameters in (1) gives the following values for the stellar flare energies converted to cosmic-ray energies:

$$F_{\mathrm{M}} = 5.8\times10^{20}\,\mathrm{J\,s^{-1}\,pc^{-3}} \text{ for the M stars,}$$

$$F_{\mathrm{K}} = 2.1\times10^{22}\,\mathrm{J\,s^{-1}\,pc^{-3}} \text{ for the K stars.}$$

6. Comparison with the total cosmic-ray energy

The values for the cosmic-ray flux from the stars derived in §5 can now be compared with the observed total cosmic-ray energy. According to a recent review by Meyer (1969) the total cosmic-ray energy in the Galaxy is 10^{-19} J cm^{-3}, requiring an energy input of 5×10^{-33} J cm^{-3} s^{-1}. Taking the volume of the galactic disk as 3×10^{66} cm^3 this corresponds to a total cosmic-ray energy input in the Galaxy of 1.5×10^{34} J s^{-1}. For comparison with the calculated output from the M and K stars it will be convenient to express the cosmic-ray energy input as the requirement per cubic parsec. Since 1 pc^{-3} is 2.9×10^{55} cm^3 the required figure is 1.5×10^{23} J s^{-1} pc^{-3}.

This value applies to cosmic-ray energies up to 10^{20} eV. We are concerned here with an upper energy limit based on the assumption that the accelerating mechanism for the stellar flares is similar to that which applies in the solar flares. The review by Fichtel & McDonald (1967) summarizes the solar flare related cosmic-ray spectrum compared with that of the total cosmic-ray spectrum. The solar cosmic rays are almost entirely concentrated in the energy region below 10^9 eV. For the highest energy flares the particle flux of the solar cosmic rays falls below that of the galactic component in the vicinity of about 3×10^8 eV. The question is therefore the extent to which cosmic-ray related events on the M and K stars may contribute to the energy requirements below this energy limit. Although the cosmic-ray spectrum is well determined for energies greater than about 3×10^8 eV (i.e. particle flux $\propto E^{-2.5}$), the exponent for lower energies is uncertain. A reasonable estimate from the data given by Fichtel & McDonald and by Meyer would appear to be that about 10% of the total galactic flux lies in the energy range below 3×10^8 eV. The cosmic-ray flux to this limit is then 1.5×10^{22} J s^{-1} pc^{-3}. If the limit is raised to 10^9 eV the spectrum is better determined and the appropriate values are 70% of the total galactic flux or 10^{23} J s^{-1} pc^{-3}. The comparison of these energy requirements with the values of F_M and F_K derived in §5*d* are given in table 8.

TABLE 8. RATIO OF COMPUTED COSMIC-RAY ENERGY FROM M AND K TYPE STELLAR FLARES TO GALACTIC COSMIC-RAY ENERGY

energy range/eV	observed galactic cosmic-ray energy flux/J s^{-1} pc^{-3}	ratio for M type stars	ratio for K type stars
10^6–3×10^8	1.5×10^{22}	0.039	1.40
10^6–10^9	1.0×10^{23}	0.006	0.21
10^6–10^{20}	1.5×10^{23}	0.004	0.14

7. DISCUSSION

The figures in table 8 indicate that the flares on the M and K type stars may be a major source of the low energy cosmic rays in the Galaxy at least for energies in the range 10^6–3×10^8 eV, and that the K stars may contribute a fifth of the total cosmic-ray energy to 10^9 eV. The assessment is based fundamentally on the recent evidence from simultaneous radio and optical observations that the flares are initiated by magnetic field collapse. In this connexion it is significant that the work of Bopp & Evans (1973) on M type stars in the quiescent state lead to identical conclusions about the role of magnetic fields in the stellar disturbances. The argument that the physical processes of flare production must be the same as in the Sun is strengthened by the circumstance that the ratio of energy produced in the flare over 10^3 MHz in the radio waveband to the bolometric energy has the same value (10^{-5}) for the M stars, the K stars and the Sun. It would, indeed, be a remarkable coincidence if this ratio, over six orders of magnitude in wavelength and over the range of stellar types from M to G, was associated with dissimilar processes. The production of cosmic rays by the M and K type flares then appears as a natural consequence, as implied in the theoretical considerations advanced by Parker (1957) to account for the cosmic-ray production in the solar flares.

The flare energy calculations have been based on systematic measurements of stars covering the appropriate absolute magnitude range. The most uncertain part of the estimates concerns the fraction of the flare energy converted to cosmic rays. In this connexion the following additional comments can be made:

(*a*) In §5*c* we have adopted a value for the conversion efficiency of solar bolometric flare energy to cosmic-ray energy of 10^{-2} on the authority of the summaries by Fichtel & McDonald (1967) and Kiepenheuer (1965). Although this figure may represent an average value for the cosmic-ray associated solar flares so far observed it must be remarked that this applies to events where the eruptive process is energetically equivalent to only about 10^{-6} of the normal energy emission from the Sun. It has been emphasized in §2 that for the star flares we have an entirely different situation where the flare energy release is of the same order as the normal quiescent energy release in the star. The assumed value of ρ may be too low when applied to the star flares, and in support of this possibility the work of Meyer, Parker & Simpson (1956) and of Parker (1957) on the cosmic-ray event associated with the large solar flare of 23 February 1956 may be mentioned. In this case the bolometric flare energy was estimated to be 2×10^{25} J, and the cosmic-ray energy *above* 3×10^9 eV was 1.4×10^{23} J. Including the cosmic rays less than 3×10^9 eV the total energy was 3×10^{23} J. Hence, even in this case of a major solar event the appropriate value for ρ is $1\frac{1}{2}$ times greater than the figure assumed in §5*c*.

(*b*) This factor ρ for the conversion of flare energy to cosmic-ray energy has, in any event, to be derived empirically from the experience with the solar flares. The difficulty that the solar flare energy is a bolometric measure whereas the reliable stellar flare energies used in §5 are in narrow band U.B.V. has been discussed in §2. Clearly the eventual assessments of the cosmic-ray energies from the stars are sensitive to the assumptions made about the U.B.V. to bolometric conversion factor for the stellar flares. The quiescent factor is clearly established – and on the basis of Kunkel's studies (1970) reasons have been given in §2 for taking a factor seven times greater than the quiescent value. This lies within the lower range of the limits suggested by Kunkel and has the implication that about 1% of the time integrated bolometric energy of the star is expended in flare energy – a result derived by Kunkel (1973) over a wide luminosity range of flare stars. The conversion factor of 10^2 assumed in §2 and §5*b* seems to be the most reasonable value to take on the basis of our present knowledge of the stellar flares. However, it may be too low. In particular the work of Bopp & Evans (1973) on the quiescent M type stars leads them to conclude that 10% of the quiescent energy of the star is available for release during the flare phase.

Hence, of the two most uncertain quantities in the assessments which lead to the figures in table 8, there is reason to believe that in both cases the assumed factors may be too low. However, even with these modest assumptions it seems realistic to believe that the flares on the K and M stars make significant contributions to the low energy cosmic rays in the Galaxy. It is realized that this conclusion is in conflict with the assessments of previous authors – for example Parker (1957) – that the overall stellar contribution to the galactic cosmic rays is insignificant. However, these previous assessments have been made on the basis that the Sun is typical in the energy which is produced during the flare phase – an assumption which is now known to be erroneous by several orders of magnitude.

It is a pleasure for me to acknowledge the help and advice which I have had from my colleagues at Jodrell Bank during the observations of the flare stars, and I particularly wish to thank Professor F. G. Smith, F.R.S., and Dr R. D. Davies for their advice on the contents of this paper.

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Discussion

T. Gold (*Space Sciences Building, Cornell University, Ithaca, New York* 14850 *U.S.A.*). The flare stars surely make a contribution to the cosmic rays. What Sir Bernard has just told us documents that and will further increase the interest in flare stars.

To see whether this contribution can be a major one, one would want to make estimates of the total mean power in the Galaxy that can be poured out into fast particles by flare stars. My guess is that it is unlikely to be a major contribution, seeing that the total power output of all the M dwarfs is itself not much more than the required 10^{34} J s^{-1} of the cosmic-ray galactic input. But of course only a small fraction of their luminous power output is put into the mechanical energy of convection. And only a fraction of that in turn appears as flare energy. The fast particles are again only a part of that. Starting in the total energy budget with little to spare, I would judge that one must end up well below the figure of 10^{34} J s^{-1} for the energetic particle supply. This of course does not detract from the interest that this phenomenon must have for cosmic-ray physicists, either as an example occurring on a more energetic scale elsewhere or as an injection mechanism for an as yet inadequately understood Fermi type mechanism.

D. Lal (*P.R.L. Ahmedabad*, *India*). If low energy cosmic rays indeed originate in numerous sources that live as long as 10^7–10^8 years, the archaic cosmic-ray record I discussed can easily be understood. In our studies, we are dealing with low energy particles of energy < 1.5 GeV/nucleon; these particles could conceivably be accelerated by red dwarfs if their flares are much more energetic than the solar flares which, on an average basis, produce protons of energies below 200 MeV in numbers appreciably larger than the corresponding galactic flux at 1 AU. Of course it remains for one to carefully see what fraction of 'low' energy cosmic rays can be produced by red dwarfs.

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