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FLARE ACTIVITY ON T TAURI STARS

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ABSTRACT

Observations of short-period photometric fluctuations in T Tauri stars show flarelike events. These events are consistent with the superposition of many solar-like flare events and have a power-spectrum frequency dependence of $\sim f^{-2}$. This dependence is the same as that observed on UV Ceti stars. The flare events are very powerful, and the expected proton flux from these events may explain early solar system abundance anomalies without recourse to nearby supernovae. The flare events are consistent with the observations of mass loss in these stars.

Subject headings: stars: flare — stars: pre–main-sequence

I. INTRODUCTION

Association with nebulosity, proximity to some OB associations, high lithium abundance, rapid rotation, and an inferred position above the main sequence in the H-R diagram all point to an early evolutionary state for the T Tauri stars, as reviewed by Herbig (1962). Cohen and Kuhi (1979), in an extensive study of pre–main-sequence objects, show that a typical T Tauri star can be represented by a roughly 1 $M_\odot$, 10–100 $L_\odot$ object on a convective evolutionary track with an age of 3×10^6 years. A detailed description of the T Tauri phenomena remains controversial, however, and no generally accepted picture of the atmospheric structure of these stars has emerged.

The observed properties of these stars have been applied to extended envelopes with considerable mass loss (Kuhi 1964; Kuan 1975), to deep stellar chromospheres (Dumont *et al.* 1973; Cram 1979), and to shock-induced emission in an accreting model (Ulrich 1976). Rydgren, Strom, and Strom (1976) discuss evidence pointing to a hot-envelope/cool-photosphere model but their use of abnormally large values of R in determining the intrinsic energy distributions of these stars has been questioned by Cohen and Kuhi (1979).

In part, the bewildering variety of spectroscopic and photometric peculiarities observed in these stars makes difficult any detailed theoretical description. High-resolution (0.25 Å) hydrogen emission-line profiles show a variety of structure, with most Hα profiles showing blue-displaced absorption features (Schneeberger, Worden, and Wilkerson 1979). The observations of Edwards (1979), however, indicate that higher Balmer series lines can show red-displaced absorption components at the same time that Hα shows a blue-displaced component. It is difficult to understand such observations in any of the models.

Despite these difficulties, the evolutionary picture of these stars as essentially young solar-type stars makes an understanding of their atmospheric conditions important not only to pre–main-sequence stellar evolution, but also to interpreting the cryptic record on the early history of the solar system. Herbig (1978) has outlined some of the pitfalls which may result from the T Tauri–solar analogy, but he does not discuss one aspect of solar phenomena which may help to explain some of the observed properties of these stars: the solar flare. Several authors have introduced the concept of solar-like flare activity in interpreting spectroscopic and photometric properties of T Tauri stars. Ambartsumian (1971) considered release of concentrated energy sources in T Tauri atmospheres, while Gordon (1958) and Gurzadyan (1973) considered the production of energetic particles (as observed in solar flares) from "active regions." More recently, Kuan (1975, 1976) has proposed that essentially continuous flaring on these stars can account for the intensity of the Balmer continuum, while maintaining a small Balmer jump, as observed, in an extended, expanding model of T Tauri atmospheres. In this model the high-density flare "blobs" produce the optically thick Balmer continuum and then expand to fill the envelope and produce the emission-line formation region.

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In this paper we present observations of flarelike activity on T Tauri stars. We show that the frequency distribution of flare amplitudes is essentially that for UV Ceti stars, and that this distribution can be understood as the superposition of many solar-like flares. We show that this interpretation of T Tauri stars as very active young solar-type stars can also be used to understand the observed abundance anomalies in the solar system, and is consistent with inferred mass-loss rates determined from expanding models.

We detail the observational program in § II and describe the flare-frequency analysis in § III. Section IV discusses the consequences of the particle flux expected from these flares, based on solar flare scaling, and the implications for solar-system abundance anomolies. We summarize our results in § V.

II. OBSERVATIONS

The program to monitor the short-term Johnson *U* band variability of T Tauri stars was carried out at the Cloudcroft Observatory. The site and telescope have been described by Schneeberger *et al.* (1979*a*). We give here a detailed description of the photometric system currently in operation at the Newtonian focus of the 1.2 m telescope.

The photometer is a single-channel pulse-counting system with provisions for eight aperture and eight filter selections. An ITT FW-130 (S-20) photomultiplier is housed in a thermoelectric cooling unit, and output pulses are fed directly to an SSR model 1120 pulse amplifier/discriminator. Output pulses are than counted by a 32 bit, 85 MHz SSR model 1108 photon counter. The photometer is controlled by an IBM 1800 computer which writes the digital data to magnetic tape and to a real-time display unit. The software clock is set with a Datum Time Translater Model 9310 which decodes a UTC time signal broadcast from White Sands Missile Range. Propagation delay has been calibrated, yielding an accuracy of ± 5 μs. At present, integration times from 10 ms to 99.9 s are available.

Sequential integrations, with integration times ranging from 3 to 10 s, using a 30″ aperture, were obtained on five T Tauri stars for durations ranging from 30 minutes up to 2 hours. Table 1 lists the 13 individual runs discussed in this paper. The star name, the date of observation, the UT times of the beginning and end of a run, and the integration times are listed in columns (1)–(5), respectively, of Table 1.

Observations of standard stars were made both before and after the observation of a T Tauri star. The standard star observations consisted of sequential integrations in the Johnson *U* band for periods ranging from 30 to 60 minutes. The standard stars were of similar *U* band brightness and covered the same range in air mass as the T Tauri stars. Sky observations were recorded during all observations at approximately 15 minute intervals. Sky measurements were subtracted from the data, which were then corrected for extinction. A preliminary discussion of the data has been given by Schneeberger *et al.* (1979*b*), where a plot of the very "active" star RW Aur is shown.

Figure 1 shows the observational data for runs on five different stars. The data show a great range in activity. RW Aur exhibits the greatest variability, followed by BP Tau. The one observation of DK Tau revealed an approximate 5% brightness increase which persisted for roughly 20 minutes. GW Ori showed no photometric fluctuations, and in fact the GW Ori data is typical of our standard star observations. The local scatter in the GW Ori data is consistent with the expected photon noise. The rms scatter due to photon noise is less than 1% for all stars except DK Tau, where the expected scatter is 1.5%. The ratio of star counts to sky counts ranged from 10 for RW Aur to 2 for DK Tau.

Monotonic increases and decreases were also observed in the stars showing activity, with short-term brightness fluctuations superposed on the trends. These observations show events which we associate with the flaring processes postulated by Kuan (1975, 1976). We proceed in the next sections to analyze the amplitude spectrum of these events and their implications.

TABLE 1

LOG OF OBSERVATIONS

Star (1)	Date (2)	UT Start (3)	UT End (4)	Integration Time (s) (5)
RW Aur	1978 Dec 10	8:02:52	8:39:46	3
RW Aur	1978 Dec 11	6:11:48	7:33:48	3
RW Aur	1978 Dec 15	8:02:52	8:39:46	3
RW Aur	1978 Dec 21	5:54:20	6:30:56	3
RW Aur	1978 Dec 21	6:51:33	7:26:33	3
RW Aur	1979 Jan 05	3:37:40	4:12:58	3
RW Aur	1979 Jan 05	4:18:38	4:48:56	3
DK Tau	1978 Dec 22	3:25:50	4:26:40	10
T Tau	1978 Dec 10	3:16:42	3:46:57	3
T Tau	1978 Dec 15	6:34:24	7:56:00	3
BP Tau	1978 Dec 05	8:44:25	9:03:10	5
BP Tau	1978 Dec 10	3:54:50	4:24:50	3
GW Ori	1979 Jan 05	5:07:05	5:42:35	3

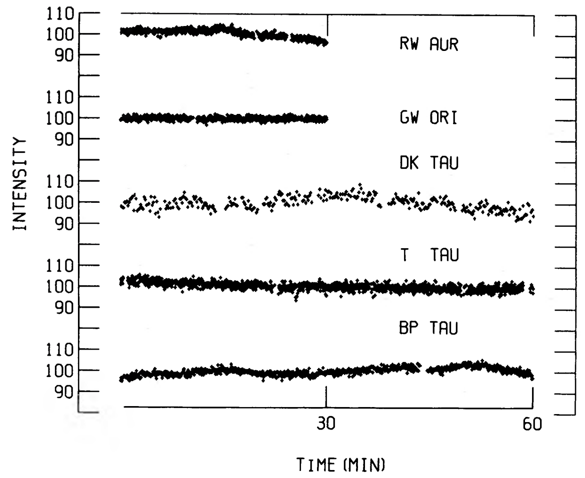

FIG. 1.—Observations of photometric fluctuations on T Tauri stars. RW Aur (1979 Jan 5, 03^h37^m) shows a UV Ceti-type "slow flare" event. GW Ori (1979 Jan 5, 05^h07^m) shows no evidence of flare activity. DK Tau (1978 Dec 22, 03^h25^m) shows a 20 minute event of roughly 5% amplitude. T Tau (1978 Dec 15, 06^h34^m) shows a slight decline in intensity, and BP Tau (1978 Dec 5, 08^h44^m) shows pronounced activity. These examples typify the range of activity observed in the T Tauri stars.

III. DATA ANALYSIS

We desire to know the total energy in the flares and how this scales with flare duration. Following Kuan (1976) we use power-spectrum analysis of the photometry. To review briefly the Fourier analysis involved, we may represent our photometric data by the standard Fourier integral:

$$I(t) = \int_{-\infty}^{\infty} \tilde{I}(f) e^{-2\pi i f t} df . \qquad (1)$$

The Fourier transform of $I(t)$, denoted by $\tilde{I}(f)$, where f is in frequency units, is computed from $I(t)$ by the inverse Fourier transform

$$\tilde{I}(f) = \int_{-\infty}^{\infty} I(t) e^{2\pi i f t} dt . \qquad (2)$$

In general, $\tilde{I}(f)$ is a complex function which may be decomposed into real amplitude $A(f)$ and complex phase $e^{i\theta(f)}$:

$$\tilde{I}(f) = A(f) e^{i\theta(f)} . \qquad (3)$$

For discrete data with N equally spaced points over a time interval T,

$$\tilde{I}(f_k) = \frac{T}{N} \sum_{j=1}^{N} I(t_j) e^{2\pi i f_k t} , \qquad (4)$$

with frequency spacing $Tf_k = 0, 1, 2, \ldots, (N/2) - 1$. The power spectrum $P(f_k)$ is usually used to display Fourier amplitude information:

$$\begin{aligned} P(f_k) &= |\tilde{I}(f_k)|^2 \\ &= A(f_k)^2 . \qquad (5) \end{aligned}$$

To determine the total energy in the photometric fluctuations we compute the integral over the amplitudes $A(f_k)$ for the frequency ranges of interest. We normalize this integral to the mean intensity level over our observation period, which is the amplitude value at zero frequency (Bracewell 1965). The flare energy is therefore

$$E_{\text{flare}} = \frac{\int_{f_1}^{f_2} A(f) df}{A(0)} . \qquad (6)$$

The parameters we desire are the total energy in the flares and the correlation of flare energy versus duration. Kuan (1976) found that T Tauri power spectra could be well represented by a power law,

$$P(f_k) \propto f_k^{-\beta} , \qquad (7)$$

where $\beta \approx 1.7$, and that this value is valid for both short-term and long-term T Tauri photometric variations. This value contrasts with $\beta \approx 2$ for flares on UV Ceti-type stars (Kunkel 1973). Kuan's value for short-term variability is based on only one power spectrum, determined from five observations of DR Tau. Kuan's (1976) determination of β for long-term (2 year) variability is based on U, B, and V magnitudes for eight stars. This long-term variability has been identified with the presence of many "active regions," or hot spots, on the stellar surface.

To determine β from our photometric data we must recognize that the data contain a substantial noise component. Since this noise is photon noise it produces a flat, frequency-independent signal in the power spectrum. We computed power spectra for our data using a Fast Fourier Transform (FFT) computer algorithm. These results are displayed in Figure 2 for a representative

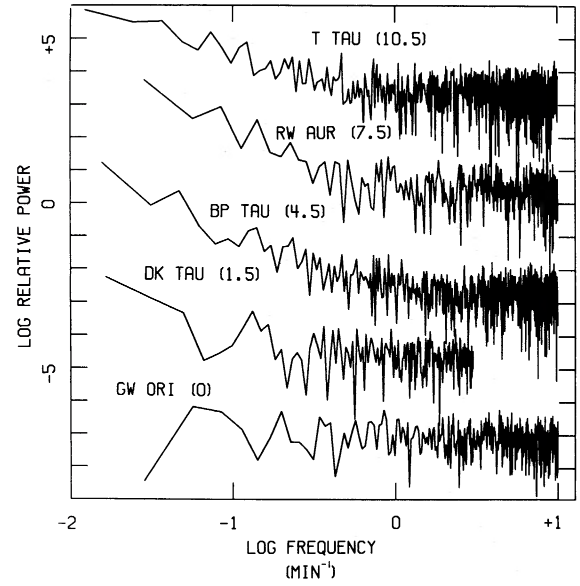

FIG. 2.—Power spectra for the five observations shown in Fig. 1. The numbers in parentheses are the powers of 10 that the power has been multiplied by. The power has been normalized to unity at zero frequency. Note the low frequency power observed in the active stars and the flat power spectrum of GW Ori, a star where no flarelike activity was seen.

sample of our data. For clarity, we display log power versus log frequency. The noise signal shows up as the flat portion of these plots at high frequency. These spectra may be represented as a sum of the frequency-dependent signal and a noise contribution:

$$P(f_k) = \alpha f_k^{-\beta} + \gamma \,, \tag{8}$$

where α is a normalization constant. We note that for one star, GW Ori, there seems to be no variability other than noise. This shows up in the power spectrum as a completely flat signal which is easily seen in Figure 2. To derive values of α and β for the other stars we take the logarithm of equation (8),

$$\log P(f_k) = \log(\alpha f_k^{-\beta} + \gamma) \,, \tag{9}$$

which reduces to

$$\log P(f_k) = \log \alpha - \beta \log f_k \tag{10}$$

for low frequencies, where γ is negligible. This relation is a simple straight line, and we have computed a straight-line least-squares fit for the low frequencies to derive α and β values. Table 2 lists β for our observations.

The mean value of β, weighted by the errors in the individual observations listed in Table 2, is 1.99, where all data except the GW Ori observation have been included. This value compares well with Kunkel's (1973) flare-star determinations, but is significantly larger than Kuan's (1976) T Tauri value. The mean error of an observation, weighted by the individual errors listed in Table 2, is ±0.21, yielding a weighted error in the mean of ±0.06. However, the data in Table 2 indicate that β is not constant. The two observations of T Tau obtained 5 days apart show significantly different values of β. The six observations of RW Aur obtained over a month also indicate changes in β, but to a lesser extent than the T Tau data. The two observations of BP Tau also indicate changes in β over a 5 day period. Since β is a measure of flare, and hence chromospheric activity, we may expect, based on solar analogy, that the level of flare activity is not constant, but related to activity cycles. Changes in 5 day periods may be due to dominant active regions. Further photometric observations are clearly needed to address the fundamental causes of variable activity in these stars. We adopt the weighted average value of β in order to study the expected consequences of this flare activity on T Tauri stars. Since this does differ from β for long-term variations, we conclude that long- and short-term variability arise from different mechanisms. We postulate that the short-term variability is due to "flares" and that the long-term changes arise from the evolution and rotation of solar-type active regions. These flares are considerably larger than solar flares. A lower limit to the optical flare energy in these stars is obtained by assuming that all flare optical energy is in the *U* band. A 5% *U* band increase lasting 10 minutes yields about 10^{34} ergs for a T Tauri flare, compared with about 10^{31} ergs of optical flare energy for the largest solar flares (Allen 1973).

TABLE 2

DERIVED RESULTS OF T TAURI POWER SPECTRUM ANALYSIS

Object	Date	β	Total *U* Band Flare Energy
RW Aur	1978 Dec 10	2.17 ± 0.26	0.107
RW Aur	1978 Dec 11	2.06 ± 0.07	0.046
RW Aur	1978 Dec 15	1.70 ± 0.20	0.041
RW Aur	1978 Dec 21	2.58 ± 0.96	0.070
RW Aur	1978 Dec 21	1.89 ± 0.21	0.027
RW Aur	1979 Jan 05	2.30 ± 0.29	0.077
RW Aur	1979 Jan 05	2.50 ± 0.27	0.015
DK Tau	1978 Dec 22	1.43 ± 0.61	0.041
T Tau	1978 Dec 10	1.51 ± 0.18	0.013
T Tau	1978 Dec 15	2.54 ± 0.33	0.095
BP Tau	1978 Dec 05	2.17 ± 0.28	0.051
BP Tau	1978 Dec 10	1.63 ± 0.20	0.080
GW Ori	1979 Jan 05	0.33 ± 0.70	...

To derive the total flare energy we need to integrate equation (6). Noting that the Fourier amplitudes $A(f_k) = [P(f_k)]^{1/2}$, we substitute our derived values for α and β into this equations and integrate. Since $\beta \approx 2$ this equation integrates to nearly a ln *f* function. The time limits we place on this integration are therefore important. For our high-frequency limit we will adopt the frequency corresponding to our shortest integration time, 3 s. The low-frequency limit presents a more serious problem. From the change of slope between long- and short-term variability, we concluded that "flares" were short-term phenomena. We therefore restrict ourselves to time scales about the same as our observing time, namely 100 minutes. This result is consistent with the longest time scales observed in both solar and flare-star flares. The results of this calculation are listed in Table 2.

It is evident that approximately 5% of the total *U* band flux from T Tauri stars is due to flare events. We can now estimate the total optical flare energy radiated in the T Tauri phase. Using Johnson's (1966) calibration of the *UBV* system and a distance of 150 pc to the Taurus-Aurigae clouds, we determined the stellar *U* band luminosity from the apparent *U* magnitude. Adopting $m_u \approx 12.00$ for T Tauri from Rydgren, Strom, and Strom (1976), we find L_u (star) $= 1.3 \times 10^{32}$ ergs s^{-1}. Assuming that these flare events are similar to UV Ceti–type flares as indicated by the similar values of β, we determine the total flare optical luminosity following Lacy, Moffett, and Evans (1976):

$$L_{\rm opt} \approx 2.4 L_u(\text{flare}) \tag{11}$$

or

$$L_{\rm opt} \approx 2.4 \times 0.05 L_u(\text{star}) \,. \tag{12}$$

Based on an approximate lifetime for the T Tauri phase of 6×10^6 years (Cohen and Kuhi 1979), we derive about 3×10^{45} ergs of optical flare energy radiated during the T Tauri phase of evolution.

IV. DISCUSSION

The surprisingly large *U* band T Tauri flare energies may be evidence for a large nonthermal particle flux. Such a flux would be an important factor in determining the observed isotopic abundances because of possible spallation reactions in the presolar isotopic mix (Fowler, Greenstein, and Hoyle 1961; Reeves, Fowler, and Hoyle 1970; Schramm 1971; Clayton, Divek, and Woosley 1977; Lee 1978; Dwek 1978, and references therein). Exact predictions and tests of the irradiation model are made difficult by a number of factors. Some of the complications are (1) the initial presolar isotopic composition; (2) the duration and nucleosynthetic history between galactic synthesis and the commencement of stellar-induced spallation; (3) the duration, flux, and spectrum of stellar energetic particles; (4) the dynamics of the preplanetary soup, e.g., the condensation time scale for planetesimals, and mixing and density distribution of material in stellar orbit; and (5) the fractionation and implantation history of postspallation planetary and asteroidal material. In this discussion we will concentrate on the third point—the assumption that the Sun evolved through a T Tauri phase and that present solar-flare activity may be scaled to estimate T Tauri particle fluences.

We will first discuss the power-law behavior of these T Tauri spectra and their relation to solar-flare light curves. To estimate the validity of our scaling arguments we will briefly sketch some of the flare models. We then estimate the relative total solar-flare energy and average proton flux. From these numbers, and data on the solar-particle energy spectrum, we get an estimate of the high-energy particle flux from these stars. We then observe that the expected stellar proton fluences are remarkably consistent with the fluence requirements of many of the high-energy particle irradiation model isotopic abundance calculations in the literature. Finally, we note that stellar mass loss due to flare activity is consistent with mass loss determinations based on the blueshifted absorption components seen in the Hα profiles of many of these stars (Kuhi 1964; Schneeberger 1977).

The principal flare products of interest for nucleosynthesis are high-energy particles. Alpha and neutron irradiation are probably important to isotopic production (Fowler, Greenstein, and Hoyle 1961; Dwek 1978; Clayton, Dwek, and Woosley 1977) as products of stellar or flare shock acceleration, and heavier nuclei may be important (Reeves, Fowler, and Hoyle 1970) as galactic cosmic rays. Because of the relative lack of nonproton flux and energy measurements, we focus on estimating the proton irradiation. We feel that this is justified since the α intensity is proportional to the proton intensity at high energies in roughly the same proportion as the solar He to H photospheric abundance ratio (Lanzerotti and MacLennan 1971), which is roughly at the 10% level. Although predicted (Lingenfelter *et al.* 1965), a significant neutron flux has not been detected from the Sun (see Svestka 1976). Furthermore, the effect of a neutron flux on early isotopic composition depends critically on the presolar dynamical model because of the neutron's large thermal capture cross section (Fowler, Greenstein, and Hoyle 1961). The discussion of such dynamical models is beyond the scope of this paper, and we limit our discussion to the proton flux expected from flares on T Tauri stars.

In attempting to scale T Tauri flare activity to solar flares we note two differences. Most important is the extreme rarity of continuum solar flares contrasted to the *U* band activity observed in our data. A more reconcilable distinction is the qualitative difference between the T Tauri light-curve variations and typical solar-flare light curves, in particular the continuous and rather smooth variability, as contrasted to an occasional flare spike on an otherwise flat solar light curve.

We can show that a power-law spectrum, similar to our data, may be produced by the superposition in time of many solar-like flare light curves. Many soft X-ray or Hα solar flares are characterized by a very rapid luminosity increase followed by a gradual decline (Dodson and Hedeman 1968). For simplicity we suppose the *U* band intensity from a typical flare varies as a function of time, characterized by two parameters, x and y, so that

$$\begin{aligned} I(t; x, y) &= y(1 - t/x) \quad \text{for} \quad t \le |x| \\ &= 0 \qquad\qquad\quad \text{for} \quad t > |x| \,. \end{aligned}$$

Here x determines the flare duration, and y is the amplitude. While this sawtooth description is a rather crude approximation, it may reasonably describe average flare properties.

We expect the observed light curve to be a superposition in time, x, and y, so with $O(t)$, the total light intensity function, and $W(\tau; x, y)$, a weighting function describing the interval between flare events, we have

$$O(t) = \iiint I(t + \tau; y, x) W(\tau; x, y) d\tau dy dx \,. \tag{13}$$

With the Fourier transform of $I(t)$ as

$$\tilde{I}(\omega) = \frac{2y}{\omega}\left(e^{i\omega x} + \frac{i \sin x\omega}{\omega x}\right),$$

we have as the observed power spectrum,

$$|\tilde{O}(\omega)|^2 \le \iint \frac{4y^2}{\omega^2}\left(\frac{\sin^2 \omega x}{\omega^2 x^2} + \frac{2 \sin^2 \omega x}{\omega x} + 1\right) \times |\tilde{W}(\omega; x, y)|^2 dy dx \,. \tag{14}$$

We assume flares occur randomly but with some characteristic time interval. For fixed x and y, $\tilde{W}(\omega)$ represents the transform of a series of unevenly spaced delta functions in time (flare occurrence times). We assume that variations in the weighting function over the observed power-spectrum domain are independent of the power-law nature of the intensity. Characteristic flare intervals may be dependent on flare amplitudes (y) and/or durations (x). However, Kunkel (1973) finds that, for flares on UV Ceti–type stars, the flare durations, while dependent on stellar luminosity, are independent of amplitude, and that active and quiet stars are found at all luminosities in the dMe range. Following our suggestion that T Tauri "flares" are similar to flares on the dMe stars, we conclude that the relationship of the amplitude and duration parameters to W, and the integration over these parameters, will probably not affect the power spectrum greatly. We see from equation (14) that for flare durations comparable to or larger than $1/\omega$ the leading term in the light-curve power spectrum goes as ω^{-2}, although the exact x and y dependence of W may to some extent affect the leading ω dependence. We observe that $\beta = 2$ is consistent with most of the observations, implying that $\omega x \gtrsim 1$ so that many of these stellar flares have characteristic times in the range 10^2–10^4 s. We conclude that T Tauri light curves are the superposition of many solar-type flares.

In order to investigate reasons for the greatly increased flare energy and continuum emission in T Tauri stars over solar activity we must first consider the source of such flare activity.

It is generally accepted that T Tauri stars are young pre–main-sequence objects lying near the Hayashi track on the H-R diagram (Rydgren, Strom, and Strom 1976). Broad photospheric absorption lines are interpreted as evidence of large rotational velocities (Herbig 1957). Such highly convective and rapidly rotating stars may be expected to generate dynamo magnetic fields. (We may also wonder what has become of any trapped interstellar magnetic field, as these stars are recently condensed from a protostellar cloud.) It is likely that magnetic fields play an important role in the dynamics of these objects and that these fields are much stronger than on the Sun (see Mullan 1974). Gershberg (1977) has suggested that the existence of strong local magnetic fields and star spots on T Tauri stars may explain a range of observable properties of these stars. The most likely source of T Tauri flare energy, as in the Sun, is the annihilation of magnetic fields. The dissipation of the associated currents through the effective inductance of, for instance, a magnetic flux tube geometry, in typical solar-flare time scales can inductively generate the required large voltages needed to explain observed solar-flare electron kinetic energies (Colgate 1978). The energetics of the current dissipation combined with some thermal conduction losses are also consistent with observed flare plasma temperatures.

If the particle acceleration is related to the thermal energy of a flare (as it seems to be for solar flares and as suggested by the above), then we have some estimate of the uncertainty in the particle flux by understanding the uncertainties in the calculated flare energies. The probability of a solar proton event has been shown to correlate well with the peak soft X-ray flux (Svestka 1970). Unfortunately, we cannot measure the X-ray flux of T Tauri stars, but instead measure continuum luminosity variations from these stars. If the T Tauri X-ray to optical luminosity ratio ($L_x/L_{\rm opt}$) is much different from the solar value we may expect our particle flux estimates to be affected. Mullan (1976) has argued that $L_x/L_{\rm opt}$ is determined by the ratio of the radiative to conductive time scales in the stellar atmosphere. He finds that $L_x/L_{\rm opt}$ in UV Ceti–type flares is probably a factor of 3 smaller than in solar flares and may be an order of magnitude lower. Recent measurements in UV Ceti stars indicate that this ratio may in fact be much larger and may vary by at least an order of magnitude between different events (Kahn *et al.* 1979). We cannot rule out the possibility of $L_x/L_{\rm opt}$ being greatly different in T Tauri stars from its solar value, although we are somewhat consoled by Mullan's model, which predicts that $L_x/L_{\rm opt}$ increases with magnetic field (which may be large for T Tauri stars). It is evident that the uncertainties in this ratio, and probably in the proton flux, are at least an order of magnitude.

From the relative total solar-flare energy ($L_{\rm flare}/L_\odot$), relative T Tauri flare energy (Table 1), and average solar proton flux we will estimate the T Tauri proton flux. We first estimate the relative solar-flare activity for comparison with the T Tauri data in Table 1.

Kahler (1978) has determined the size and emission measure of 45 solar flares during 1973. Using the average flare energy from his sample and an average solar maximum flare rate from Smith and Smith (1963) gives a rough estimate of the mean flare thermal radiation of 3×10^{25} ergs s^{-1}. Dryer (1974) notes that the total flare energy (including shock wave, hard X-rays, etc.) is probably not more than an order of magnitude more than the thermal radiation. With Allen's (1973) value of the solar luminosity we find a rough value for the relative flare energy of 7×10^{-8}.

The mean proton intensity during a solar maximum year may be estimated from the proton flare incidence, the measured proton intensity associated with each flare, and the mean flare duration. From Svestka (1975, 1976) the average proton flux (> 10 MeV) from the Sun during the solar maximum year of 1968 and an average proton flare duration may be determined. Assuming a triangular time dependence for the flux from these flares as indicated by the representative results of Van Hollebeke, Ma Sung, and McDonald (1975), we find an average intensity of 10 MeV or greater solar protons to be roughly 2×10 cm^{-2} sr^{-1} s^{-1} at 1 AU. From Gambosi *et al.*'s (1977) measurements it is evident that the propagation of flare protons is a complex and highly variable process between different flare events. The complicated diffusion process makes it difficult to estimate the net average proton irradience at 1 AU from these local intensity averages. Uncertainties in this measurement and anisotropy in the actual intensity lead us to use 1% of the above intensity to estimate a yearly average irradiation at 1 AU of 3×10^{28} MeV or greater protons s^{-1}. We expect that a proton flux derived in this fashion should scale with the flare radiation over a solar activity cycle. Using Svestka's (1975) proton flare catalog, and Smith and Smith's (1963) flare incidence data, we find that this is indeed the case. Although the data are from different activity cycles we find that the proton fluence tracks the Hα flare incidence to within an order of magnitude.

The energy spectrum of solar protons shows great variability between proton events. Van Hollebeke, Ma Sung, and McDonald (1975) fitted a power-law spectrum to the differential flux of the form $dJ/dE \sim E^{-\gamma}$ with mean γ of 2.9 for 20–80 MeV protons. The maximum likelihood γ is a function of energy, solar longitude of the event, and time interval between the flare and measurement. Proton energies as high as 15 GeV have been inferred from some flares (the 1956 February flare; Svestka 1975). Flare differential particle flux is evidently a strong function of the total flare energy. Hudson (1978) has noted that if Van Hollebeke's flare event versus proton intensity distribution and Drake's flare event versus soft X-ray flux distribution are treated as simultaneous observations, then a flare's peak proton flux would vary as the 5.6 power of its flare energy. Although these inferences were not drawn from the same population, there seems to be a statistical association between energetic flares and high-intensity proton events. This helps to reassure us that if T Tauri flares are as energetic as solar flares then scaling linearly from solar activity will not underestimate either the net flux or peak energy proton flux.

The proton irradiation is derived by scaling the relative stellar-flare energy from the corresponding solar ratio and multiplying by the relative solar proton flux and stellar luminosity. Taking the *U* band relative flare energy of each source as representative of the total flare energy, and Rydgren, Strom, and Strom's (1976) calculations of the stellar luminosities, we estimate irradiation rates of from $6 \times 10^{35} > 10$ MeV s^{-1} for T Tau to 6×10^{34} s^{-1} for BP Tau. These figures correspond to a flux at 1 AU of from 2×10^8 to 2×10^7 cm^{-2} s^{-1}.

We compare these crude flux estimates with the particle fluences required to produce some of the observed isotopic abundance ratios. We assume an upper bound to the duration of the T Tauri phase of 10^7 years, the evolutionary time for a Population I 1 $M_{\odot}$ star to reach a luminosity minimum, and a characteristic convective stage time scale (Iben 1965). Although the early model of Fowler, Greenstein, and Hoyle (1961) may have ignored what we now know to be large isotopic composition differences in solar-system material, his proton flux and energy needed to produce the observed lithium, beryllium and boron abundances are probably more than met by T Tauri flare activity. They require 10^{45} ergs of 500 MeV nucleons, while based on the above arguments we expect T Tau can supply at least 10^{47} ergs of energetic protons. If the energy spectrum approximates $(dJ/dE \sim E^{-\gamma}$, with $\gamma \lesssim 2.5$, 10^{45} ergs of 500 MeV or greater protons are provided. Schramm (1971) has discussed the importance and production of ^{26}Al in the early solar system and found that a fluence of at least 4×10^{18} cm^{-2} is needed to provide the mass of ^{26}Al useful as a heat source in planetary objects. This fluence would be attainable over 10^4–10^5 years. Heymann and Dziczkaniec (1976) and Audouze *et al.* (1976) have discussed possible explanations for ^{26}Mg anomalies. While the low energy flux of 10^{17}–10^{19} protons cm^{-2} yr^{-1} of Heymann and Dziczkaniec is two orders of magnitude greater than what we would estimate, it is certainly within reach. On the other hand Audouze *et al.* (1976) can explain the ^{22}Ne and magnesium anamolies by supposing a fluence of $\sim 10^{18}$ low-energy protons cm^{-2}, although this result may imply a constraint on the high-energy particle flux. Clayton, Dwek, and Woosley (1976) have discussed the production of other isotopic abundances and also have shown that a consistent description of the observations demands constraints on the mixing, condensation or implantation history of early solar material. Lee (1978) has argued that the ^{22}Al and ^{16}O measurements may be explained by assuming that a small fraction of the solar material sees a fluence of $\sim 2 \times 10^{25}$ cm^{-2} so as not to upset measured Mg, Ca, and Ba abundances. Again, we find this fluence is attainable for material near the Sun. Dwek (1978) has considered the effect an α flux would have on the ^{41}K abundance and has suggested a possible test of the irradiation hypothesis, although a nonhomogeneous irradiation history and uncertainties in the mixing fractionation and formation histories of the grains might provide alternative solutions.

It is evident that most of the isotopic abundance calculations involving an early stellar high-energy particle irradiation are consistent with our T Tauri particle flux estimates. The major alternative to the irradiation hypothesis depends on the injection of *r*-process isotopes into the early solar system by a nearby supernova (see Margolis 1979). While estimates based on T Tauri energetics cannot refute the supernova theory, we find the consistency of the irradiation models with the flux estimates considerably more satisfactory than appealing to the special circumstances of a supernova to explain the abundance anomalies.

It is notable that vigorous T Tauri flare activity may also help to explain other T Tauri characteristics.

Our conclusion that the short-term photometric variability in T Tauri stars is a representation of very energetic solar-type flares can also be used to estimate a mass-loss rate. By scaling the integrated mass flux behind the shock front from the 1978 August 7, solar flare, as a yearly average, by the factor we used to scale the solar proton irradiation to T Tauri stars, we determine the flare-induced mass loss in these stars. From Zastenker *et al.*'s (1978) value of $\sim 2 \times 10^{-16}$ $M_{\odot}$ yr^{-1} for the 1978 August 7 event, we find a mass-loss rate of $\sim 4 \times 10^{-9}$ $M_{\odot}$ yr^{-1} from flare events on T Tauri stars. The calculations of mass-loss rates for T Tauri–type stars have invoked extended geometries and large outflow velocities to reproduce relative line strengths (Kuan 1975). The existence of forbidden lines in emission in T Tauri spectra, requiring $N_e \sim 10^4$ cm^{-3}, indicates that in fact very extended geometries are involved. Moreover, the stellar wind velocity observations of Schwartz (1975) and the velocity field mapping based on line center wavelength coincidence and subsequent pumping by Willson (1974, 1975) indicate large-scale velocity fields extending outward from T Tauri stars. Ulrich (1976) has criticized Kuan (1975) for basing his calculations on incorrect collisional rates and neglecting cross-talk between spherical shells in a decelerating model. Schneeberger (1977) has performed new calculations which account for cross-talk and includes correct collisional rates, and he finds a mass-loss rate of $\sim 6 \times 10^{-9}$ $M_{\odot}$ yr^{-1} in excellent agreement with the expected flare-induced mass-loss rate. In addition, Kuan (1975) has postulated that the observed Balmer continuum emission from T Tauri stars can be understood consistently with an extended, expanding model of the T Tauri envelope, if many higher-density "blobs" are ejected near the surface. Our observations show that the photometric fluctuations of these stars can be understood as essentially continual flaring, and that these flare events can account for the T Tauri mass loss deduced from extended models.

V. CONCLUSIONS

U band photometric fluctuations have been interpreted in terms of flare activity on T Tauri stars. The photometric fluctuations have a power-spectrum frequency dependence of $\sim f^{-2}$. Such a spectrum is expected from the superposition of many solar-like flare light curves. The range of time scales for individual flares on T Tauri stars is 10^2–10^4 s, also similar to solar-flare time scales. Individual flares are more energetic than solar flares. The flare activity accounts for approximately 5% of the total *U* band luminosity of the T Tauri stars, with individual events being 10^3 times more energetic than large solar flares. Flare activity on T Tauri stars is thus more frequent and more energetic than solar flare activity. The observed activity, with significant changes in the power-spectrum frequency dependence detected in 5 day intervals. Further photometric observations are necessary to understand the relationship of the variable activity to possible solar-like activity cycles.

The total proton flux expected from the flares is consistent with the irradiation model for solar isotopic abundance anomalies, thus precluding the necessity for a nearby supernova. The flare events are also consistent with the mass-loss estimate based on violet-displaced absorption features in Hα line profiles.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone).

Ambartsumian, V. A. 1971, *Astrofizika*, **7**, 557.

Audouze, J., Bibring, J. P., Dran, J. C., Maurett, M., and Walker, R. M. 1976, *Ap. J.* (*Letters*), **206**, L185.

Bracewell, R. N. 1965, *The Fourier Transform and its Applications* (New York: McGraw Hill).

Clayton, D. D., Dwek, E., and Woosley, S. E. 1977, *Ap. J.*, **214**, 300.

Cohen, M., and Kuhi, L. V. 1979, *Ap. J. Suppl.*, submitted.

Colgate, S. A. 1978, *Ap. J.*, **221**, 1068.

Cram, L. E. 1979, preprint.

Dodson, H. W., and Hedeman, E. R. 1968, *Solar Phys.*, **4**, 229.

Dryer, M. 1974, *Space Sci. Rev.*, **15**, 403.

Dumont, S., Heideman, N., Kuhi, L. V., and Thomas, R. N. 1973, *Astr. Ap.*, **29**, 199.

Dwek, E. 1978, *Ap. J.*, **221**, 1026.

Edwards, S. 1979, *Pub. A.S.P.*, **91**, 329.

Fowler, W. A., Greenstein, J. L., and Hoyle, F. 1961, *Geophys. J. R.A.S.*, **6**, 148.

Gambosi, T., Kòta, J., Gomogyi, A. J., Kurt, V. G., Kuzhevskii, B. M., and Logachev, Yu. I. 1977, *Solar Phys.*, **54**, 441.

Gershberg, R. E. 1977, *IAU Highlights of Astronomy*, Vol. **4**, Part 2, ed. E. Muller (Dordrecht: Reidel), p. 407.

Gordon, I. M. 1958, *Astr. Zh. USSR*, **35**, 458.

Gurzadyan, G. A. 1973, *Astr. Ap.*, **28**, 147.

Herbig, G. H. 1957, *Ap. J.*, **125**, 612.

———. 1962, *Adv. Astr. Ap.*, **1**, 47.

———. 1978, in *The Origin of the Solar System*, ed. S. F. Dermott (New York: Wiley), p. 219.

Heymann, D., and Dziczkaniec, M. 1976, *Science*, **191**, 79.

Hudson, H. S. 1978, *Solar Phys.*, **57**, 237.

Iben, I. 1965, *Ap. J.*, **141**, 993.

Johnson, H. L. 1966, *Ann. Rev. Astr. Ap.*, **4**, 193.

Kahler, S. W. 1978, *Solar Phys.*, **59**, 87.

Kahn, S. M. *et al.* 1979, preprint.

Kuan, P. 1975, *Ap. J.*, **202**, 425.

Kuan, P. 1976, *Ap. J.*, **210**, 129.

Kuhi, L. V. 1964, *Ap. J.*, **140**, 1409.

Kunkel, W. E. 1973, *Ap. J. Suppl.*, **25**, 1.

Lacy, C. H., Moffett, T. J., and Evans, D. S. 1976, *Ap. J. Suppl.*, **30**, 85.

Lanzerotti, L. J., and MacLennan, C. G. 1971, in *Proc. COSPAR Symp.*, 1969 Nov. *Sol. Part. Event*, p. 85 (see Svestka 1975).

Lee, T. 1978, *Ap. J.*, **224**, 217.

Lingenfelter, R. E., Flamm, E. J., Canfield, E. H., and Kellman, S. 1965, *J. Geophys. Res.*, **70**, 4087.

Margolis, S. H. 1979, *Ap. J.*, **231**, 236.

Mullen, D. 1974, *Ap. J.*, **192**, 149.

———. 1976, *Ap. J.*, **207**, 289.

Reeves, H., Fowler, W. A., and Hoyle, F. 1970, *Nature*, **226**, 727.

Rydgren, A. E., Strom, S. E., and Strom, K. E. 1976, *Ap. J.*, **30**, 307.

Schneeberger, T. J. 1977, Ph.D. thesis, New Mexico State University.

Schneeberger, T. J., Worden, S. P., Africano, J. L., and Tyson, E. 1979*a* *Sky and Tel.*, in press.

———. 1979*b*, *Bull. AAS*, **11**, 439.

Schneeberger, T. J., Worden, S. P., and Wilkerson, M. S. 1979, *Ap. J. Suppl.*, **41**, 369.

Schramm, D. N. 1971, *Ap. Space Sci.*, **13**, 249.

Schwartz, R. D. 1975, *Ap. J.*, **195**, 631.

Smith, H. J., and Smith, E. P. 1963, *Solar Flares* (New York: MacMillan), p. 71.

Svestka, Z. 1970, *Solar Phys.*, **13**, 471.

Svestka, Z. 1975, *Catalog of Solar Particle Events, 1955–1969* (Boston: Reidel).

———. 1976, *Solar Flares* (Boston: Reidel).

Ulrich, R. K. 1976, *Ap. J.*, **210**, 377.

Van Hollebeke, M. A. I., Ma Sung, L. S., and McDonald, F. B. 1975, *Solar Phys.*, **41**, 189.

Willson, L. A. 1974, *Ap. J.*, **191**, 143.

———. 1975, *Ap. J.*, **197**, 365.

Zastenker, G. N., Temny, V. V., D'uston, C., and Bosqued, J. M. 1978, *J. Geophys. Res.*, **83**, 1035.