1up

X-660-74-5
PREPRINT

NASA TM X-70568

NEUTRON PROPAGATION AND 2.2 MeV GAMMA-RAY LINE PRODUCTION IN THE SOLAR ATMOSPHERE

H. T. WANG
R. RAMATY

JANUARY 1974

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

(NASA-TM-X-70568) NEUTRON PROPAGATION AND 2.2 MeV GAMMA-RAY LINE PRODUCTION IN THE SOLAR ATMOSPHERE (NASA) 20 p HC $3.00 CSCL 03B

N74-15476

Unclas
G3/29 27041

NEUTRON PROPAGATION AND 2.2 MEV GAMMA-RAY LINE PRODUCTION IN THE SOLAR ATMOSPHERE

H. T. Wang
Department of Physics and Astronomy
University of Maryland
College Park, Maryland, USA

R. Ramaty
Goddard Space Flight Center
Greenbelt, Maryland, USA

ABSTRACT

We have calculated the 2.2 MeV gamma-ray line intensity from the Sun using a Monte-Carlo method for neutron propagation in the solar atmosphere. We provide detailed results on the total gamma-ray yield per neutron and on the time profile of the 2.2 MeV line from an instantaneous and monoenergetic neutron source. The parameters which have the most significant effects on the line intensity are the energies of the neutrons, the position of the neutron source on the Sun, and the abundance of He^3 in the photosphere. For an isotropic neutron source which is not too close to the limb of the Sun, the gamma-ray yield is between about 0.02 to 0.2 photons per neutron, provided that the neutron energies are in the range 1 to 100 MeV and the ratio He^3/H is less than about $5x10^{-5}$.

I. Introduction

Gamma-ray line emissions at 0.51, 2.2, 4.4, and 6.1 MeV were observed by Chupp et al. (1973) during the flare of August 4, 1972. These emissions are believed to be due to positron annihilation, deuterium formation by neutron capture on hydrogen, and the deexcitation of excited states in C^{12} and O^{16} (Lingenfelter and Ramaty 1967, Ramaty and Lingenfelter 1973).

The calculation of the line intensities from excited nuclei is in general straightforward because the deexcitations occur in a much shorter time scale than any of the characteristic times of the solar flare. However, because the time scales associated with positron annihilation and neutron capture in the solar atmosphere could be comparable with the characteristic times of the flare, the calculation of line intensities at 0.51 and 2.2 MeV has to take into account in detail the production, slowing down, and annihilation or capture of positrons or neutrons. In this paper we present a calculation on the formation of the 2.2 MeV line from neutrons in the solar atmosphere.

The principal modes of neutron production in solar flares are nuclear reactions of accelerated particles with the ambient solar atmosphere (Lingenfelter et al. 1965). Typically, the neutrons have energies between 1 and 100 MeV, but their number and energy spectrum depend on the intensity, composition, and the spectrum of the accelerated charged particles and the composition of the ambient medium in the flare region. Some of the effects of these variables were investigated by

Lingenfelter and Ramaty (1967) and Ramaty and Lingenfelter (1973). However, in calculating the gamma-ray yield at 2.2 MeV, these authors have assumed that all downward moving neutrons are captured by protons, that all the upward moving photons escape from the Sun, and they have neglected neutron capture on photospheric He^3.

In this paper we present corrections to these simplifying assumptions. We find that some of the downward moving neutrons decay or escape before capture, and that He^3 can constitute an important non-radiative sink for the neutrons. Furthermore, some of the upward moving photons are lost from the 2.2 MeV line by Compton scattering. We also calculate the time profile of the 2.2 MeV line intensity from an impulsive release of neutrons at the Sun, and we show how these calculations can be used to find the time-dependent 2.2 MeV line intensity from an arbitrary solar neutron source.

II. Method of Calculation

We consider the instantaneous release of monoenergetic neutrons with given angular distribution at a given height, h, above the photosphere. By using a Monte-Carlo method, we follow the path of each neutron in the solar atmosphere. This path is terminated by decay, escape or capture. For those neutrons which get captured by protons, we record the elapsed time from release to capture, and the depth in the solar atmosphere where the capture takes place. Thus, we can calculate the probabilities for decay, escape, and capture, the attenuation of the gamma rays, and the time profile of the gamma-ray burst. The details of the calculation are given in the Appendix. Here we only present our assumptions and approximations. The results are presented in the next section.

We assume that the neutrons are produced in the chromosphere or lower corona where the flare accelerated particles are expected to interact with the solar atmosphere. Then the value of h is small compared to the radius of the Sun, and hence the solar atmosphere can be treated as a plane stratified medium. However, because the exact value of h is not known, we treat it as a free parameter.

Both the temperature and density in the atmosphere are functions of height, and we have used the tabulation of Allen (1963) for these quantities. The principal interactions between the neutrons and the solar atmosphere are elastic scattering and capture. Because of the relative abundances of the constituents of the solar atmosphere and their cross sections, elastic scattering is mainly due to ambient protons, but neutrons are captured on both protons and helium-3. The cross section, σ_s, for elastic scattering is essentially constant at $2 \times 10^{-23} cm^2$ from 1 eV to 10^5 eV, and then it drops to about $10^{-25} cm^2$ at 100 MeV (Hughes and Schwartz 1958). The cross section for capture on protons is inversely proportional to velocity and is given by $\sigma_c(H) \approx 2.2 \times 10^{-30} \beta^{-1} cm^2$, where $c\beta$ is the relative velocity between the neutron and the proton. The capture cross section on He^3 has the same form as that on H, and is given by $\sigma_c(He^3) = 3.7 \times 10^{-26} \beta^{-1} cm^2$ (King and Goldstein 1949).

Only upper limits are available on the He^3 abundance in the photosphere. In the solar wind, the ratio He^3/H is about 5×10^{-5} (Geiss and Reeves 1972). In our calculation we use as limiting values

$He^3/H = 5 \times 10^{-5}$ and $He^3/H = 0$.

In neutron-proton elastic scattering we assume a uniform angular distribution for the recoil neutron in the center of mass system. This is valid for neutrons of energies less than 10 MeV. In the 10 to 100 MeV range, the distribution is approximately symmetric about 90°, and the assumption of uniform distribution does not effect significantly the final probabilities.

In calculating the gamma-ray line intensity at Earth from the reaction $n+p \to d+\gamma$ at the Sun, we assume that the gamma rays are produced isotropically. The principal interaction between 2.2 MeV photons and the solar atmosphere is Compton scattering. From the Klein-Nishina formula, $\sigma_{KN}(2.2\ \text{MeV}) = 1.4 \times 1.0^{-25}\text{cm}^2$.

III. Results and Discussion

The probabilities for decay, escape, and capture on protons and loss on He^3 are shown as solid lines in Figures 1 and 2 for $He^3/H = 5 \times 10^{-5}$ and $He^3/H = 0$, respectively. In these calculations the neutrons were released at $h = 3 \times 10^9$ cm above the photosphere with a uniform angular distribution. Because the calculations are insensitive to the exact value of h as long as it is much smaller than one solar radius, we do not show results for other values of h.

The capture and loss probabilities increase with increasing energy, because at higher energies the neutrons penetrate deeper into the photosphere. This prevents them from escaping and reduces the escape probability; it also leads to a shorter capture time, thereby reducing the decay probability. When $He^3/H = 5 \times 10^{-5}$, the probability for loss on He^3 almost equals the capture probability on protons. The escape probability is greater than 0.5, because all initially upward moving neutrons escape from the Sun. Note that the sum of all probabilities equals 1.

Now we consider the gamma-ray intensities. Let $\phi(t-t_o,\theta,E_n)$ be the time profile at Earth of the 2.2 MeV gamma-ray line from one neutron of energy E_n released at time t_o at the Sun measured in photons $cm^{-2}sec^{-1}$, where θ is the angle between the earth-sun line and the vertical to the plane stratified medium. We define the photon yield per neutron, $f(\theta,E_n)$, as

$$f\ (\theta,E_n) = 4\pi R^2 \int_{t_o}^{\infty} \phi(t-t_o,\theta,E_n)dt \ , \qquad (1)$$

and we show it by the dashed lines in Figures 1 and 2.

At low neutron energies and θ near zero, f is close to the capture probability on protons. This means that gamma rays from low-energy neutrons observed close to the vertical escape essentially unattenuated from the Sun. At higher energies and at larger angles, however, there is significant attenuation of the gamma rays.

In previous calculations, it was assumed that all downward moving neutrons are captured and that all upward moving photons escape from the Sun. In this case f should equal 0.5. However, from Figures 1 and 2 we see that, depending on the energy of the neutrons, the location of the flare on the Sun (which determines the angle θ), and the amount of He^3 in the photosphere, this assumption can overestimate the gamma-ray yield by at least a factor of 2.5. Furthermore, if the flare occurs close to the limb of the Sun, the 2.2 MeV line becomes essentially unobservable. For such limb flares, however, the 0.51 MeV line and the nuclear deexcitation lines will still be observable because these lines are believed to be produced above the photosphere.

The function $4\pi R^2\phi$ is shown in Figures 3 and 4 for $He^3/H = 5 \times 10^{-5}$ and $He^3/H = 0$, respectively. We note that the rise times of the gamma-ray burst are less than about 25 seconds in all cases. These rise times increase with decreasing neutron energy and increase with increasing θ. We have prepared extensive tables of ϕ for a variety of values for the parameters E_n, θ, and the ratio He^3/H. These tables are available in unpublished form and will be presented in a forthcoming dissertation.

The function ϕ can now be used to calculate the time-dependent 2.2 MeV line intensity at Earth, $F(t,\theta)$, from a continuous non-monoenergetic neutron source at the Sun. Let $q\ (t_o, E_n)$ be the instantaneous rate of neutron production in the energy interval dE_n around E_n. Then $F(t,\theta)$ is given by

$$F(t,\theta) = \int_o^\infty dE_n \int_{-\infty}^t q(t_o,E_n)\ \phi(t-t_o,\theta,E_n)dt_o \quad . \tag{2}$$

In the present paper we did not carry out a detailed study of F because the observational data on the time profile of the 2.2 MeV line is rather meager. Reppin <u>et</u> <u>al</u>. (1973), however, have estimated the time-dependent 2.2 MeV intensity for the flare of August 4, 1972 by replacing $\phi(t-t_o,\theta,E_n)$ in equation 2 with the function $(4\pi R^2)^{-1}\ \exp\ [-\lambda(t-t_o)]$. Here

$\lambda = \tau_c^{-1} + \tau_d^{-1}$, where τ_c is the capture time of neutrons on hydrogen and τ_d is the mean life time of the neutron. This approach neglects the dependence of ϕ on θ and E_n, as well as the capture of neutrons on He^3; also, it does not take into account the Compton scattering of the 2.2 MeV photons. Nonetheless, an exponential function can be used as a crude approximation of ϕ provided that the capture time τ_c is approximately given by

$$\tau_c(\mathrm{sec}) \approx \frac{1.5 \times 10^{19}}{n(\mathrm{cm}^{-3})} , \qquad (3)$$

where n is the density of the ambient solar atmosphere where most of the captures take place (Ramaty and Lingenfelter 1973). These authors have argued that the bulk of the captures take place at a depth in the photosphere where the neutron suffers its first elastic scattering. Our calculations essentially substantiate this assumption and indicate that the captures take place at depths of a few hundreds kilometers below the photosphere.

APPENDIX

We now describe the method for the evaluation of the probabilities for escape, decay or capture of a neutron that is produced in the solar atmosphere, and the calculation of the depth in the photosphere where the neutron is captured by a proton. We then use this depth to determine the probability for Compton scattering of an upward moving photon resulting from this capture.

Consider a neutron of energy E_o produced at a height h_o above the photosphere at time t_o moving at a directional cosine μ_o between its velocity vector and the vertical to the plane stratified solar atmosphere. ($\mu > o$ is defined as motion upwards). Let h_j be the height at which the j^{th} elastic scattering between the neutron and an atmospheric proton has occurred at time t_j so that after the scattering the neutron has energy E_j and is moving with directional cosine μ_j. We want to find a new height h_{j+1} where the next elastic scattering could occur at time t_{j+1}. We also want to determine whether the neutron decays or is captured (on H or He^3) between h_j and h_{j+1}, and to find the neutron energy and direction after scattering at h_{j+1} provided it has not decayed or has not been captured.

In the following we shall have to determine random numbers X with distribution functions $\Phi(X)$ from uniformly distributed random numbers R, $0 \le R \le 1$, which can be generated on a computer. In the subsequent discussion all R's represent such random numbers. From the theory of probability

$$\Phi(X) = R \quad \text{and} \quad X = \Phi^{-1}(R). \tag{A1}$$

For example, for neutron decay, the lifetime of neutrons T_d, has the distribution function

$$\Phi(T_d) = 1 - \exp(-T_d/\tau_d), \tag{A2}$$

where τ_d = 15.3 minutes is the neutron mean lifetime.

Thus

$$T_d = -\tau_d \ln(1-R_d). \tag{A3}$$

Given the height h_j, the distribution function of h_{j+1} is the probability for the neutron to be scattered between h_j and h_{j+1}, i.e.

$$\Phi(h_{j+1}) = 1 - \exp\left[-\sigma_s(E_j)\left[N(h_j) - N(h_{j+1})\right]/\mu_j\right]. \tag{A4}$$

Here $\sigma_s(E)$ is the cross section for elastic scattering at energy E, and N(h) is the columnar density of the solar atmosphere above the height h. From equations (A1) and (A4) we get that

$$N(h_{j+1}) = N(h_j) + \left[\mu_j/\sigma_s(E_j)\right] \ln(1-R_{s,j}). \tag{A5}$$

By inverting $N(h_{j+1})$ we obtain h_{j+1} ; we note, however, that if $\mu_j > o$ and $N(h_j) < -\mu_j/\sigma(E_j)\ln(1-R_{s,j})$ no solution can be found. Physically this means that the neutron escapes after the j^{th} scattering.

Having found h_{j+1}, the time t_{j+1} is simply

$$t_{j+1} = t_j + (h_{j+1} - h_j)/(\mu_j v_j) \tag{A6}$$

where v_j is the velocity at energy E_j. The neutron will decay between t_j and t_{j+1} if

$$t_j < T_d < t_{j+1}. \tag{A7}$$

In order to determine whether the neutron will be captured on protons between t_j and t_{j+1} we proceed as follows. Let h_{cH} be the height at which a neutron is captured after j elastic scatterings. Applying the same considerations as for equation (A4), the distribution function of h_{cH} is

$$\Phi(h_{cH}) = 1- \left\{ \prod_{k=1}^{j} \exp\left[-\sigma_c(E_{k-1})(N(h_{k-1})-N(h_k))/\mu_{k-1}\right]\right\} \times$$
$$\times \exp[-\sigma_c(E_j)(N(h_j) - N(h_{cH})/\mu_j], \quad \text{(A8)}$$

where $\sigma_c = \sigma_c(H)$ is the capture cross section on hydrogen as a function of neutron energy. Using equations (A5) and (A8), we get that

$$N(h_{cH}) = N(h_j) + \mu_j/\sigma_c(E_j) \left[\ell n(1-R_{cH})-\sum_{k=1}^{j} \frac{\sigma_c(E_{k-1})}{\sigma_s(E_{k-1})} \ell n(1-R_{s,k-1})\right], \quad \text{(A9)}$$

where R_{cH} is another random number, and the random numbers $R_{s,k-1}$ are those which have been used to calculate h_{k-1}. Equation (A9) can be inverted ; the neutron will be captured on a proton between t_j and t_{j+1} if

$$\left|h_{cH} - h_j\right| < \left|h_{j+1} - h_j\right| . \quad \text{(A10)}$$

Similarly, the neutron will be captured on a He^3 between t_j and t_{j+1} if

$$\left|h_{cHe^3} - h_j\right| < \left|h_{j+1} - h_j\right| . \quad \text{(A11)}$$

Here h_{cHe^3} is obtained in the same manner as h_{cH}, with the exception that $\sigma_c(H)$ is replaced by $(He^3/H)\ \sigma_c(He^3)$, where He^3/H is the ratio of the He^3 to H in the photosphere. Once a neutron is captured by a proton, we record the time and depth of capture. The former is used to calculate the time profile of the burst and the latter is needed to evaluate the effects of Compton scattering on the photons. In order to obtain the energy and direction of the neutron after elastic scattering at h_{j+1} we first find the temperature at this height, and then use a Maxwell-Boltzman distribution to find the velocity components of the interacting protons (random numbers corresponding to gaussian distribution can be generated directly on a computer). We then assume that the directional cosine of the neutron is uniformly distributed in the center of mass system so that we can choose a random number R_{np} corresponding to this directional cosine. From the conservation of energy and momentum we then get the energy and direction of the scattered neutron in the frame of the Sun.

Acknowledgment

We wish to acknowledge Hubert Reeves for pointing out the importance of neutron capture on He^3. The research of H. T. Wang was supported by NASA Grant 21-002-316.

REFERENCES

Allen, C. W., 1963, Astrophysical Quantities, Athlone Press, London.

Chupp, E. L., Forrest, D. J., Higbie, P. R., Suri, A. N., Tsai, C., and Dunphy, P. D., 1973, Nature, 241, 333.

Geiss, J. and Reeves, H., 1972, Astron. and Astrophysics, 18, 126.

Hughes, D. J. and Schwartz, R. B., 1958, Neutron Cross Sections, Brookhaven National Laboratory, Upton, New York

King, L. D. P. and Goldstein, L., 1949, Phys. Rev., 75, 1302.

Lingenfelter, R. E., Flamm, E. J., Canfield, E. H., and Kellman, S., 1965, J. Geophys. Res., 70, 4077.

Lingenfelter, R. E. and Ramaty, R., 1967, High Energy Nuclear Reactions in Astrophysics (ed. by B. S. P. Shen) W. A. Benjamin, New York, p.99.

Ramaty, R. and Lingenfelter, R. E., 1973, High Energy Phenomena on the Sun, Symposium Proceedings,(ed. by R. Ramaty and R. G. Stone) X-693-73-193, Goddard Space Flight Center, Greenbelt, Md., p.301.

Reppin, C., Chupp, E. L., Forrest, D. J., and Suri, A. N., 1973, Conference Papers, 13th International Cosmic Ray Conference, University of Denver, Denver, Colorado, p.1577.

FIGURE CAPTIONS

Figure 1. Probabilities for neutron escape, decay, capture on protons and loss on He^3 in the solar atmosphere (solid lines); and photon yields per neutron (dashed lines). The parameter θ is the angle between the earth-sun line and the heliocentric radial direction through the flare. The ratio He^3/H is the photospheric helium 3 abundance, and E_n is the energy of the neutrons.

Figure 2. Probabilities for neutron escape, decay, and capture on protons in the solar atmosphere (solid lines) and photon yields per neutron (dashed lines).

Figure 3. Time profiles of the 2.2 MeV line intensity at Earth multiplied by $4\pi R^2$, where R = 1 A.U., produced by instantaneously released monoenergetic neutrons at time t_o. The rest of the parameters are the same as in Figures 1 and 2.

Figure 4. Time profiles of the 2.2 MeV line intensity at Earth multiplied by $4\pi R^2$, where R = 1 A.U., produced by instantaneously released monoenergetic neutrons at time t_o. The rest of the parameters are the same as in Figures 1 and 2.

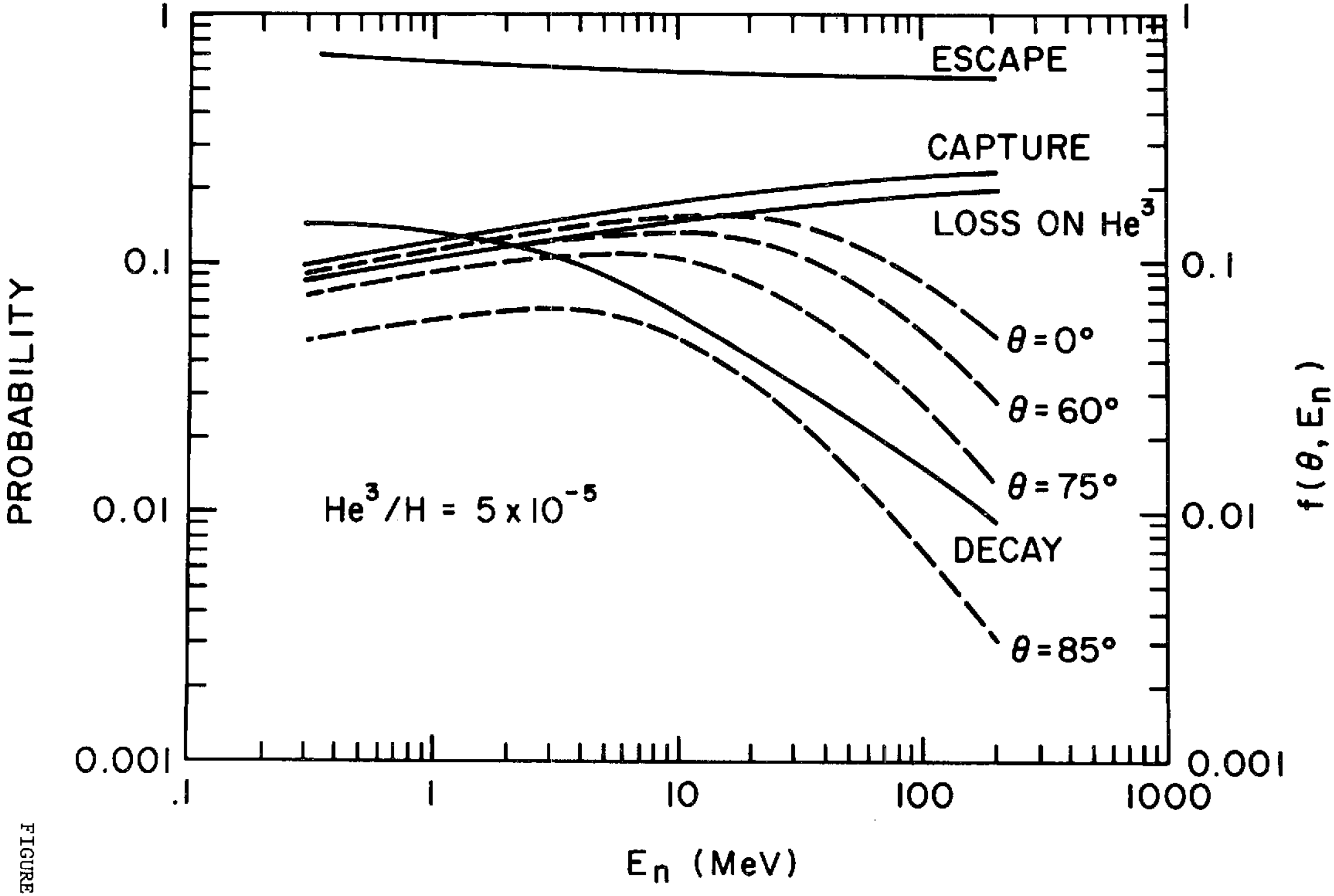

ESCAPE
CAPTURE
LOSS ON He^3
$\theta = 0°$
$\theta = 60°$
$\theta = 75°$
DECAY
$\theta = 85°$
He^3/H = 5 x 10^{-5}
PROBABILITY
$f(\theta, E_n)$
E_n (MeV)
1
0.1
0.01
0.001
.1
1
10
100
1000

FIGURE 1

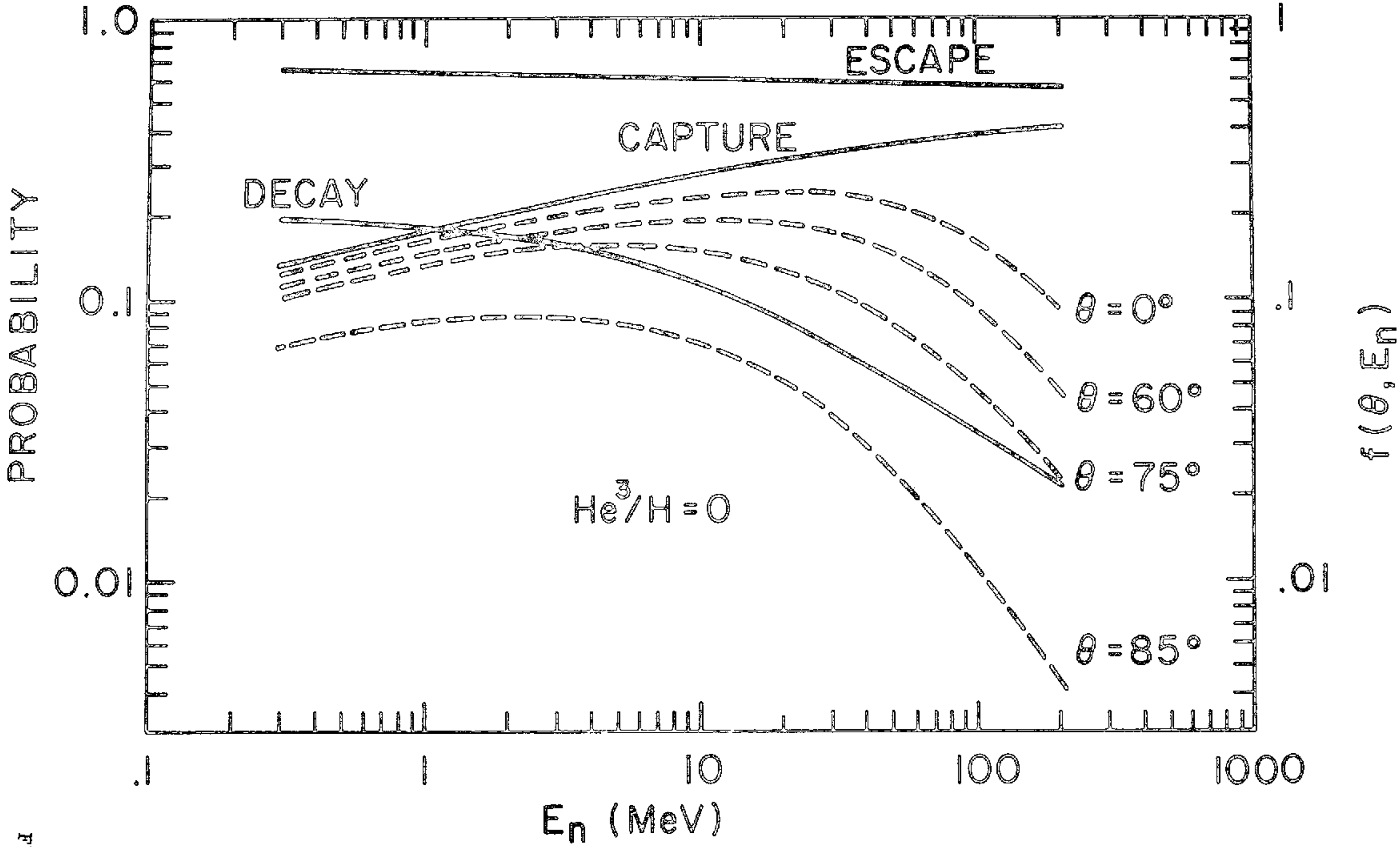
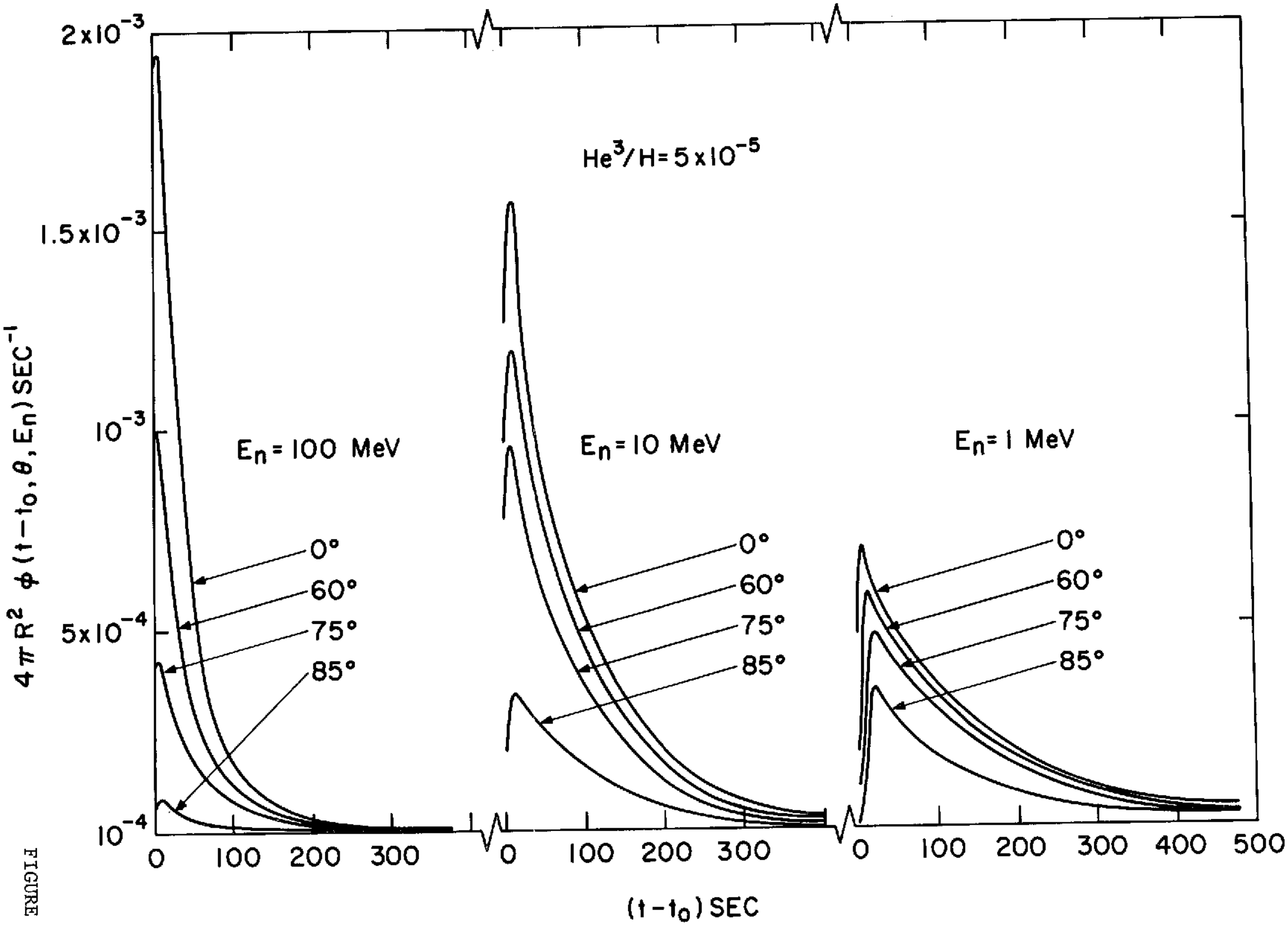
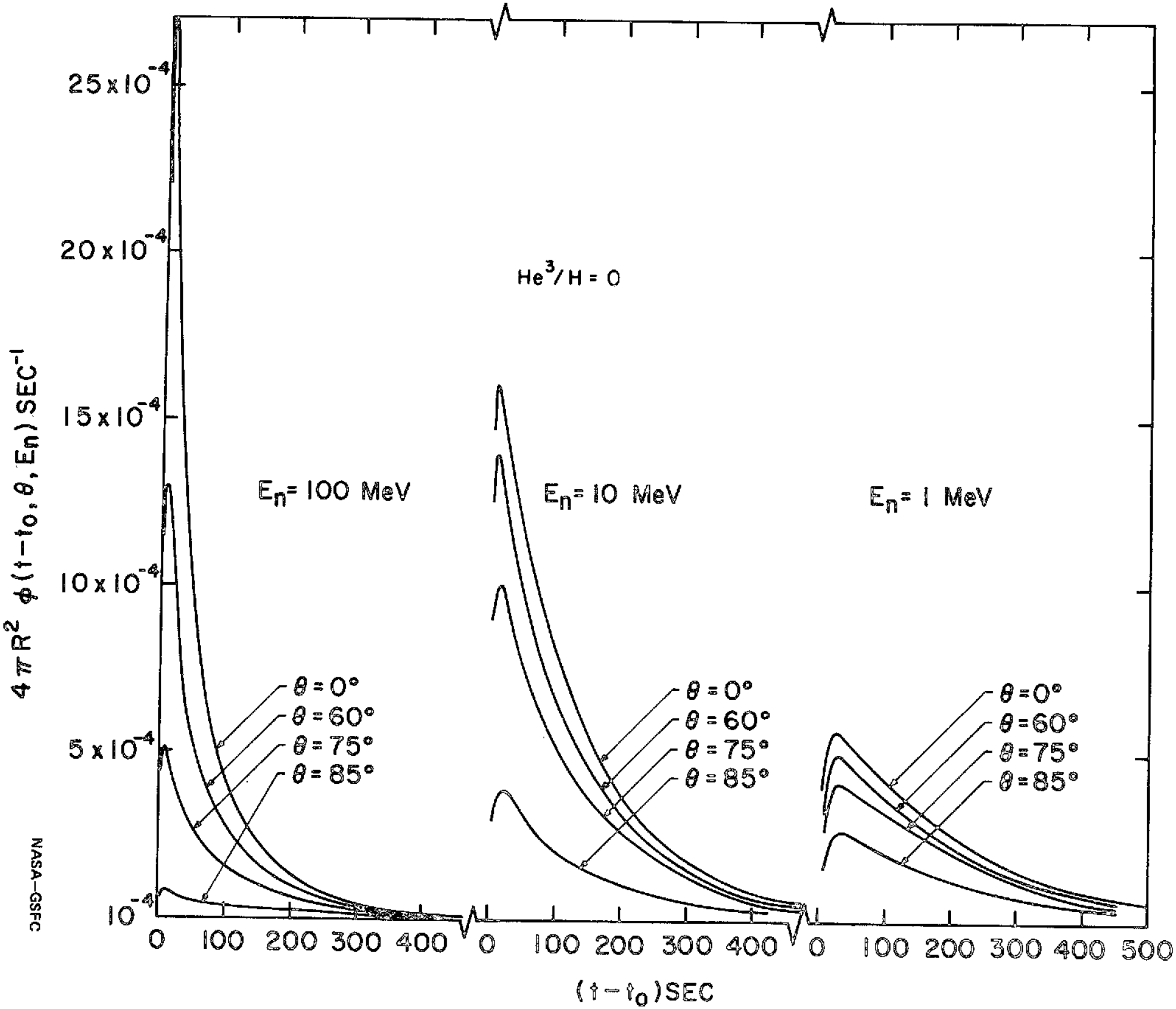

1.0
0.1
0.01
PROBABILITY
ESCAPE
CAPTURE
DECAY
θ = 0°
θ = 60°
θ = 75°
θ = 85°
He3/H = 0
1
.1
.01
f(θ, En)
.1
1
10
100
1000
En (MeV)

FIGURE 2



$He^3/H = 5 \times 10^{-5}$
E_n = 100 MeV
E_n = 10 MeV
E_n = 1 MeV
0°
60°
75°
85°
2×10^{-3}
1.5×10^{-3}
10^{-3}
5×10^{-4}
10^{-4}
0 100 200 300
0 100 200 300
0 100 200 300 400 500
$(t - t_0)$ SEC
$4\pi R^2 \; \phi(t - t_0, \theta, E_n)$ SEC^{-1}

FIGURE 3



NASA-GSFC

FIGURE 4