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Abstract

We show here that the revised measurements of galactic gamma-ray intensities as measured by OSO-3 can be accounted for by the pion-decay process in the galactic disk and by a combination of this process and Compton interactions with an intense infrared radiation field in the region of the galactic center. This interpretation is in harmony with our present understanding of the interstellar medium and obviates the need to invoke more speculative source models. It also indicates the potential use of gamma-ray telescopes in mapping the interstellar medium.

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Last year, one of us (F.W.S.)[1] put forward a hypothesis to explain the origin of the disk component of galactic gamma-radiation observed by Clark, et al.[2] using a satellite-borne detector aboard OSO-3. It was suggested that these gamma-rays result from the decay of neutral pions produced in cosmic-ray interactions with the total nucleon content of interstellar gas, much of which was hypothesized to be in the form of molecular hydrogen. Arguments were given in reference 1 to support this hypothesis, these arguments being based on recent results from other branches of astronomy dealing with the study of the interstellar medium. This paper was closely followed by a detailed presentation of the OSO-3 results by Kraushaar at the 37th I.A.U. Symposium in Rome showing that the gamma-ray spectrum from the galactic disk closely matched that of the horizon-albedo gamma-ray spectrum from the earth which arises mainly from the decay of neutral pions produced by cosmic-ray interactions with the earth's atmosphere, thus giving tentative, but not conclusive support to the pion-decay hypothesis for the origin of galactic gamma-rays.

In order to explain the gamma-ray intensity originally quoted by Clark, et al., using the pion-decay hypothesis a mean gas density in the galactic disk of the order of 5 nucleons per cm^3 was required, a value close to the upper limit allowed by galactic dynamics[3]. However, owing to a recent recalibration of the sensitivity of the OSO-3 detector, the gamma-ray fluxes originally given by Clark, et al. have been revised downward by a factor of ~ 2 (Clark, Kraushaar, and Garmire, private communication). A total nucleon density of the order of 2 cm^{-3} will provide a gamma-ray flux in the galactic disk within the accuracy of the revised observational value under the assumption of a uniform cosmic-ray intensity in the galactic disk. Since 21 cm observations[4] indicate a mean density of <u>atomic</u> hydrogen in the galactic disk of the order of 1 cm^{-3}, the gamma-ray observations indicate that

$$\langle n_{HI,cool} + 2n_{H_2} \rangle \simeq \langle n_{HI,emission} \rangle \qquad (1)$$

under the assumption of a fairly uniform cosmic-ray intensity in the galaxy.

A considerable quantity of molecular hydrogen in the interstellar medium had been considered a likely possibility until Stecher and Williams[5] found an effective mechanism for its photodestruction. It now appears that in the presence of an average interstellar radiation field, the amount of molecular hydrogen expected to be present will be negligible. Recent rocket measurements appear to support this conclusion[6,7]. In dark clouds, however, the rate of H_2 formation is expected to exceed the photodestruction rate and essentially all the hydrogen is expected to exist in molecular form. Recent observations of dark clouds[9,10] show an anti-correlation between atomic hydrogen and dust which may indicate that the hydrogen in these clouds has been converted into molecular form.

Kerr and Westerhout[4] have argued that the hydrogen contained in cool optically thick interstellar clouds can be expected to equal that seen in 21 cm emission which is a more smoothly distributed component of gas at a considerably higher temperature. Various references supporting this "raisin pudding" model of the interstellar medium were given in reference 1. Additional theoretical support for the model on the basis of dynamical stability arguments has also been given[3]. In addition, the galactic longitude distribution obtained for interstellar hydrogen from 21 cm emission measurements alone appears to be far more isotropic than our concept of the sun's position in the galaxy would indicate, again suggesting that a significant fraction of interstellar gas must be present in optically thick clouds within 10 kpc of the galactic center[4]. This argument is further strengthened by the fact that the gas to dust ratio in the interstellar medium appears to be constant and the observation of 27 magnitudes of extinction toward the the galactic center[11], implying a large quantity of interstellar gas in that direction.

Thus, the pion-decay hypothesis for the origin of the disk component of galactic gamma-radiation, as put forth in reference 1, but with a total mean nucleon density of $\sim 2\ \mathrm{cm}^{-3}$, provides a natural and adequate explanation for both the intensity and spectral characteristics of this radiation as observed by Clark, et al. The intensity distribution of this component, as a function of galactic longitude, shows only one statistically significant peak, viz., the peak at the galactic center. Observations made by detectors with better sensitivity and resolution should enable gamma-ray astronomers to map the disc component for gamma-ray "hot spots" which should reflect the true distribution of the total content of interstellar gas, independent of temperature and optical opacity conditions in various regions of the galaxy. However, we are at present limited to a general discussion of the intensity of the disk component with the possibility of an additional source component at the galactic center. The peak in the gamma-ray intensity at the galactic center, which has a line strength of $\sim 2 \times 10^{-4} \mathrm{cm}^{-2} \mathrm{sec}^{-1} \mathrm{rad}^{-1}$ above 100 MeV, as determined both by the revised OSO-3 measurements and by Fichtel, et al.[12] requires further discussion. Approximately half of these gamma-rays can be explained as due to the decay of neutral pions produced in cosmic-ray interactions with the galactic gas (the disk component we have been discussing) on the assumption that the cosmic-ray intensity is uniform throughout the galaxy. An increase in cosmic-ray intensity toward the galactic center by an additional factor of ~ 2 could thus account for the increased flux in the galactic center region. Alternatively we could introduce a "two-component" model for galactic gamma-rays in which gamma-rays from a production mechanism other than pion-decay contribute an additional flux to that produced by the general disk component. We would thus classify the galactic center as a gamma-ray source. We wish to suggest here that there may be such a source of gamma-rays produced by Compton interactions of cosmic-ray electrons with the intense infrared radiation field located at the galactic center and detected at 100μ by Hoffman and Frederick[13]. Hoffman and Frederick have found this source to extend $\lesssim 2^{\circ}\!.3$ in galactic latitude and $\gtrsim 6^{\circ}\!.5$ in galactic longitude and to have a brightness temperature of 16 K. The source has been suggested by Lequeux[14] to be produced by reradiation of intense starlight in the central region of the galaxy by interstellar grains produced in the atmospheres of red giant stars[15] with such grains being an order of magnitude more numerous in the galactic center region than in the disk. Using the infrared intensities given by Hoffman and Frederick, we find that cosmic-ray electrons with the same intensity as that observed at the earth above 3 GeV can produce a gamma-ray flux of 2-7 X 10^{-5} cm^{-2} sec^{-1} rad^{-1} above 100 MeV by Compton interactions, which is the same order of magnitude as the estimated flux from the disk-component in the galactic center region. It is thus impossible at this time to determine theoretically whether pion decay or Compton interactions could be expected to play the major role in producing gamma-rays at the galactic center under the assumptions of the two-component model presented here. The situation is further complicated by the possibility of increased fluxes of both cosmic-ray electrons and nucleons at the galactic center, although there is no need to postulate the existence of such fluxes in order to account for the observed gamma-radiation. It is also unnecessary to postulate the existence of an 8 K graybody infrared radiation field of galactic extent, a hypothesis which was invoked by Shen[16] and Cowsik and Pal[17] in order to account for the originally quoted OSO-3 measurements, and was based on a measurement of Shivanandan, et al.[18]. However, the proposed existence of this 13 eV/cm^3 radiation field poses serious theoretical problems pertaining to its origin and role in the galactic energy balance and its effect on cosmic-ray electrons[19] and ultrahigh energy cosmic-rays[20]. The 8 K hypothesis is also in grave conflict with measurements of the spin-temperatures of various molecules in the interstellar medium[21-23] and most recently has been directly contradicted by a new infrared measurement of McNutt and Feldman[24].

Based on the discussion we have just presented, we can already reach some important conclusions regarding the origin of galactic gamma-rays.

1. Gamma-rays originating in the galactic disk most likely result from the decay of neutral pions produced in interstellar cosmic-ray interactions. The excess originating in the galactic center region can be produced by a combination of the pion-decay process and Compton interactions between cosmic-ray electrons and infrared radiation.

2. The explanations offered above obviate the necessity for invoking strong gamma-ray point sources, large gradients in the galactic cosmic-ray flux, or 8 K graybody radiation fields of galactic extent in order to explain the revised gamma-ray observations.

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