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"CHESHIRE CAT" COMPTON SCATTERING AND "EXCESS CONTINUUM"

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“... אף כי אנו יודעים כי ישנם חוקים המגבילים את חופש הביטוי, אנו מאמינים כי חופש הביטוי הוא ערך יסודי במחוקקת, ויש להגביל את החוקים המגבילים את חופש הביטוי, כדי להבטיח את חופש הביטוי.”

POSITRON ANNIHILATION IN THE GALACTIC CENTER: "CHESHIRE CAT" COMPTON SCATTERING AND "EXCESS CONTINUUM"

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ABSTRACT

Two separate observations of the γ -ray spectrum originating from the Galactic Center were made by HEAO-3 in the fall of 1979 and in the spring of 1980. The 2γ 511 KeV annihilation line flux decreased by a factor of three over the corresponding six month period, whereas the excess γ -ray continuum below the 511 KeV line, often interpreted as 3γ decay of orthopositronium, barely changed. This apparent discrepancy in the temporal behavior makes it difficult to associate the bulk of the excess continuum with the 3γ decay of positronium. We will show that Compton scattering of the line and high energy radiation provides a natural explanation for the surprisingly small change seen in the excess continuum.

INTRODUCTION

The HEAO-3 observations of the Galactic Center in the fall of 1979 and the spring of 1980 established this region as a strong source of annihilation radiation.¹ The flux in the narrow 511 KeV e^+e^- annihilation line reached $\sim 10^{43}$ annihilations per second. The energy of the line was almost exactly $m_e c^2$, limiting the gravitational redshift to less than 10^{-5} . The line intensity decreased by a factor of ~ 3 over a six month period. Therefore, the annihilation region must be smaller than 10^{18} cm.² A hydrogen column density of $\rho_H \sim 0.2$ g/cm² is needed to stop a relativistic (1 MeV) positron. Using this fact and the upper limit on the size of the region we obtain a lower limit on the number density $n_H > 10^5$ cm⁻³.

In both a neutral and ionized medium, most of the positrons annihilate via the intermediate stage of a Positronium atom (Ps).^{3,4} Positronium decays from its ground state, which can be either a spin triplet (parallel spins) or a spin singlet (antiparallel spins). The spin singlet (para-Ps) decays to two 511 KeV photons, whereas the spin triplet (ortho-Ps) decays to a 3γ continuum extending to 511 KeV. The linewidth of the 511 KeV line is determined by the average velocity of the Ps atom prior to annihilation. The observed linewidth limits the cloud temperature to $T_{cloud} < 10^4$ K. Observations of the inner parsecs of the Galactic Center – extensively discussed in this volume – support the existence of HII regions with such temperatures and with number densities around 10^5 cm⁻³.

The γ -ray continuum was simultaneously measured during the HEAO-3 observations. It has been modeled by a combination of a power-law, an ortho-Ps (3γ) decay continuum, and a Comptonized thermal emission spectrum to match the observed high energy component.⁵ The fall '79 data show a high luminosity in photons of energy greater than 511 KeV. We shall refer to this portion of the spectrum as the "high-energy continuum". Photons in the energy range of 200-511 KeV, which cannot be accounted for by the extrapolation of low and high energy portions of the spectrum, are then regarded as an "excess continuum". This excess continuum was

often regarded as evidence for 3γ decays of ortho-Ps. For annihilations proceeding exclusively through Ps, the ratio of 3γ continuum to 2γ line intensity is $9/2$. Yet, the value obtained from the fall '79 data was much less than this. One of us has demonstrated that annihilation events occur predominantly on dust grains in an interstellar HII region containing the usual abundance of dust.⁶ The lifetime of the ortho-Ps atom which forms on the grain is longer than the collision time with electrons in the dust grain. Therefore, the ortho-Ps atom undergoes collisional charge exchange prior to annihilation. This exchange converts the ortho-Ps to a spin singlet para-Ps, thereby suppressing the total number of 3γ decays and explaining the low observed flux associated with the excess continuum.

Any changes in the flux of the 511 KeV line should be accompanied by similar changes in the flux associated with ortho-Ps decay. But, the spring '80 observations showed that while the line flux dropped by a factor of three, the flux associated with the three photon decay decreased only slightly. Therefore the initial interpretation of the excess continuum in terms of ortho-Ps decay radiation is in doubt. Moreover, the high energy ($E > 511$ KeV) component of the spectrum was no longer observed in the spring '80 data.

ROLE OF COMPTON SCATTERING: THE "CHESHIRE CAT" CONTINUUM

The parameters derived earlier for the annihilation region give a Compton scattering optical depth for 511 KeV photons of $\tau_{511} > 0.05$. Therefore, at least 5 percent of the line photons are Compton scattered in these HII regions on their way to Earth. The photon always loses energy in these scatterings, since the temperature of these regions is low compared to the photons' incident energy ($kT_{cloud} \ll 511$ KeV). Hence, the scattered line radiation falls in the energy range 170-511 KeV and contributes to the excess continuum. The spectrum of Compton scattered line radiation mimics that of 3γ decay, as originally pointed out by Forrest.⁷ Scattered line photons arrive at Earth at a later time than unscattered ones originating from the same point. Therefore if the positron source suddenly turned off, the observer would initially only see a reduction in the line intensity. The flux in the excess continuum below the line would not show appreciable changes until the crossing time ($t_{cross} \sim R/c$) of the photon through the annihilation region has passed. This time delay, the "Cheshire Cat" effect, explains the lack of immediate changes in the excess continuum. If one assumes that the high energy component of the spectrum ($E > 511$ KeV) originates from the region of positron production, then it must also undergo Compton scattering. In view of the similar temporal variations of the line and the high energy component, this seems reasonable. The luminosity in the high energy continuum is approximately 10 times greater than the luminosity in the line. Therefore, even for low optical depths, Compton scattering of the line plus the high energy component can naturally account for the intensity as well as for the delay in temporal variations of the excess continuum. If the optical depth is indeed so low, Compton scattering of the line alone would affect the observations only very little. Nevertheless, when one includes the high-energy component enough photons are placed in the 200-511 KeV range to account for the intensity of the excess continuum. Moreover, it is also conceivable – although we shall disregard this possibility in the remainder of this note – that the optical depth is large enough so that Compton scattered line photons could account for most of the excess continuum.

MODEL

Realistic models of the Galactic Center annihilation source are not available at present. Therefore, we will work with a simple scenario, hoping that the salient features are independent of geometry. We place the photon source at the center of a spherical cloud of constant number density n_H . The problem is then one of deriving the scattered spectrum seen by the observer as a function of time. Given the past observations of the annihilation line, it is reasonable to use a source model that was constant for a long time and then died off with a six month decay time.⁸ The observed spectrum of the excess continuum is then a function of the time since turnoff and the optical depth. The analytic calculation was done with a 0 or 1 scattering approximation and was compared to a Monte Carlo code to verify the results. We have made no attempt to fit the data with this model; this issue will be addressed elsewhere.⁹ Here we merely want to establish the importance of Compton scattering in the Galactic Center annihilation region.

Figure 1: "Cheshire Cat" continua:

- 1) Solid line - Compton scattered 2γ annihilation photons. Note the absence of higher energy radiation in the lower curve which corresponds to the later time.
- 2) Broken line - Compton scattered high energy continuum. Prominent backscatter peak appears at 220 KeV.

This calculation was done for both the line and the high energy continuum. The spectra of scattered radiation seen by the observer for these two components are shown in Figure 1. Both of the top lines correspond to a steady state (fall '79), whereas the lower lines correspond to a time six months after turnoff (spring '80). The graphs show the relative constancy of the excess continuum. To see how the "Cheshire Cat" continuum affects the γ -ray observations, we added the broken line spectra of Figure 1 to the other two continuum components used by Riegler *et al.*⁵ The spectra in Figure 2 therefore represent what would be observed if the H.E. continuum was being Compton scattered since this dominates over the line alone being scattered. The power law (P) is determined by the low energy data. The high energy component (T) was taken to be the Comptonized thermal emission derived by Sunyaev and Trümper, which is similar, but not identical to that used by Riegler.^{10,11} As in Riegler *et al.*'s analysis, the H.E. continuum was taken to have 10 times the luminosity of the line. Note the backscatter peak at 220 KeV in both the fall and the spring. These plots should be regarded only as a qualitative illustration of the phenomena.

Figure 2: The evolution of the Galactic Center γ -ray spectrum predicted by the "Cheshire Cat" continuum model. The form of the fall '79 (Figure 2a) and spring '80 (Figure 2b) spectra was obtained by assuming that the H.E. continuum originated from a cloud of optical depth ~ 0.2 and radius ~ 2 light years.

CONCLUSIONS

The role of Compton scattering in the Galactic Center cannot be ignored. It provides a very natural explanation for the two separate HEAO-3 observations. This would also imply significant annihilation on dust since the 3γ decays must be substantially suppressed to obtain the observed time variation of the spectrum. The strongest prediction that we can make is that when the source turns back on, the excess continuum should be much weaker than in the steady state and must be largely attributed to 3γ decay, since Compton scattered photons would be delayed. Further observations are clearly needed, in addition to a reanalysis of the data including the effect of Compton scattering. In particular, it may be worthwhile to reexamine the data to search for the backscatter peak near 220 KeV.

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