N92-21898

COMPTON BACKSCATTERED ANNIHILATION LINE EMISSION A NEW DIAGNOSTIC OF ACCRETING COMPACT SOURCES

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ABSTRACT

We show that Compton scattering of 511 keV electron-positron annihilation radiation produces a line-like feature at $\sim$ 170 keV from backscattered photons. Assuming a simple model of an accretion disk around a compact source, we explore the spectrum of Compton scattered annihilation line emission for a range of observing angles and disk opacities and find that the line-like feature is produced under a wide range of conditions. We further show that such Compton backscattering of annihilation line emission from the inner edge of an accretion disk could account for the previously unidentified 170 keV line emission and high energy continuum observed[1-3] from a variable, compact source, or sources, of annihilation radiation near the Galactic Center. Identification of the observed 170 keV line as an annihilation line reflection feature provides strong new evidence that the source of the emission is an accreting compact object. Further study of these features in existing spectra and in forthcoming GRO observation of these and other sources can provide unique new diagnostics of the innermost regions of accretion disks around compact objects.

INTRODUCTION

Compton scattering of x-rays and gamma rays has been studied in a variety of astrophysical sources. Comptonization of x-rays by plasma clouds has been studied in compact sources[4]. Compton reflection of the hard x-ray and gamma-ray continuum has been studied in solar flares[5] and in accretion disks around compact objects[6]. Compton attenuation of gamma-ray line emission has been studied in solar flares[7] and in supernovae[8,9]. And Compton "tails" of gamma-ray lines have been studied as a diagnostic in solar flares[10], and as a continuum source in supernovae[8,11] and an alternative to orthopositronium emission in the variable annihilation radiation source in the direction of the Galactic center[12,13].

We have recently pointed out[14] the astrophysical importance of Compton backscattering of gamma-ray lines that can produce *line-like reflection features* at lower energies. These Compton backscattered features are well-known in the laboratory, but their astrophysical significance had not been discussed previously. We considered, by way of illustration, the Compton backscattering of the 511 keV electron-positron annihilation line which produces a line-like feature at $\sim$ 170 keV. We studied the Compton scattering of 511 keV photons because they are the most nearly ubiquitous of any astrophysical gamma-ray line photons, and because 170 keV line emission has, in fact, been observed[1-3] to accompany the intense 511 keV line emission from the direction of the Galactic center.

Here we briefly discuss the generation of line-like features by Compton backscattering of the 511 keV annihilation line in the context of an accreting black hole source of the variable annihilation line emission in the region near of the Galactic center.

COMPTON BACKSCATTERING OF THE ANNIHILATION LINE

The energy of the Compton-scattered photon relative to the initial photon energy is $r = E'_\gamma/E_\gamma = 1/(1+\alpha-\alpha\cos\phi)$, where $\alpha = E_\gamma/m_ec^2$ and ϕ is the scattering angle. The energy distribution of the Compton-scattered photons is

$$f(r) \propto \left[r - 1 + \frac{1}{r} + \frac{(\alpha r + r - 1)^2}{\alpha^2 r^2}\right]$$

for $1/(2\alpha+1) \leq r \leq 1$, corresponding to scattering angles $180° \geq \phi \geq 0°$, and $f(r) = 0$ for other values of r. This distribution, which rises steeply at the lowest energies and then cuts off sharply at the 180° backscattered energy of $r = 1/(2\alpha+1)$, produces a line-like feature just above the minimum energy. This feature can be seen in Figure 1, where we show the energy distribution of Compton scattered 511 keV annihilation radiation photons. For 511 keV photons $\alpha = 1$ and the scattered photons have energies $1/3 \leq r \leq 1$, or 170 keV $\leq E'_\gamma \leq$ 511 keV, so that the scattered photon energy distribution is simply $f(r) \propto (r + 3 - 3/r + 1/r^2)$. As can also be seen in Figure 1, the backscattered photons ($90° \leq \phi \leq 180°$) are compressed into a relatively narrow energy range of 1/6 of 511 kev, while the forward scattered photons are spread over an energy range of 1/2 of 511 keV, three times larger.

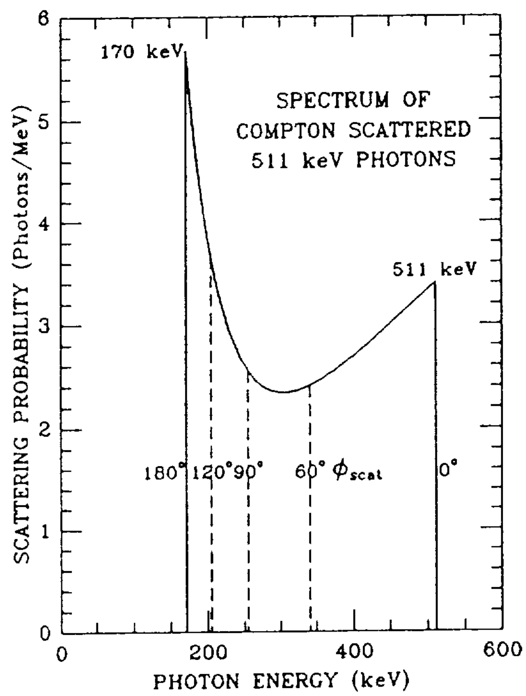

Figure 1. The spectrum of Compton scattered 511 keV photons as a function of the scattered photon energy and scattering angle, showing the line-like backscattered feature at 170 keV.

The Compton scattering distribution shown in Figure 1, of course, is only for singly scattered line photons and multiple scattering produces a broader spectrum extending down to much lower energies. To study the full spectrum resulting from multiple Compton scattering of line photons, we have made a series of Monte Carlo simulations. In all cases we assumed an isotropic, monoenergetic source of 511 keV annihilation line photons, and allowed them to Compton scatter on cold ($kT \ll m_ec^2$) electrons in a simple, uniform density, gaseous disk. In particular, we considered a disk in a cylindrical coordinate system with linear dimensions defined in terms of the Compton scattering optical depth τ at 511 keV, equivalent to 3.5×10^{24} electrons cm^{-2}. The disk was assumed to lie in a plane normal to the z axis with a thicknesses in the z direction equal to τ and a radius $\gg \tau$. In order to approximate the inner edge of an accretion disk around a compact object, we considered a cylindrical hole in the disk centered at the origin with its axis in the z direction normal to the plane of the disk. The size of the hole is defined by an opening angle θ_o which is the zenith angle of the inner edge of the disk measured with respect to the axis of the cylinder. Thus, the radius of the hole is equivalent to $\frac{1}{2}\tau\tan\theta_o$ and the limiting case of $\theta_o = 0°$ is simply the uniform disk without a hole. We have ignored disk rotation in this simple model. We also assumed for simplicity that the source of the 511 keV photons is located at the origin in the center of the hole. Thus the emerging unscattered 511 keV line intensity, as a function of μ the cosine of the observing angle θ, is equal to $1/2\pi$ for $\theta < \theta_o$, and

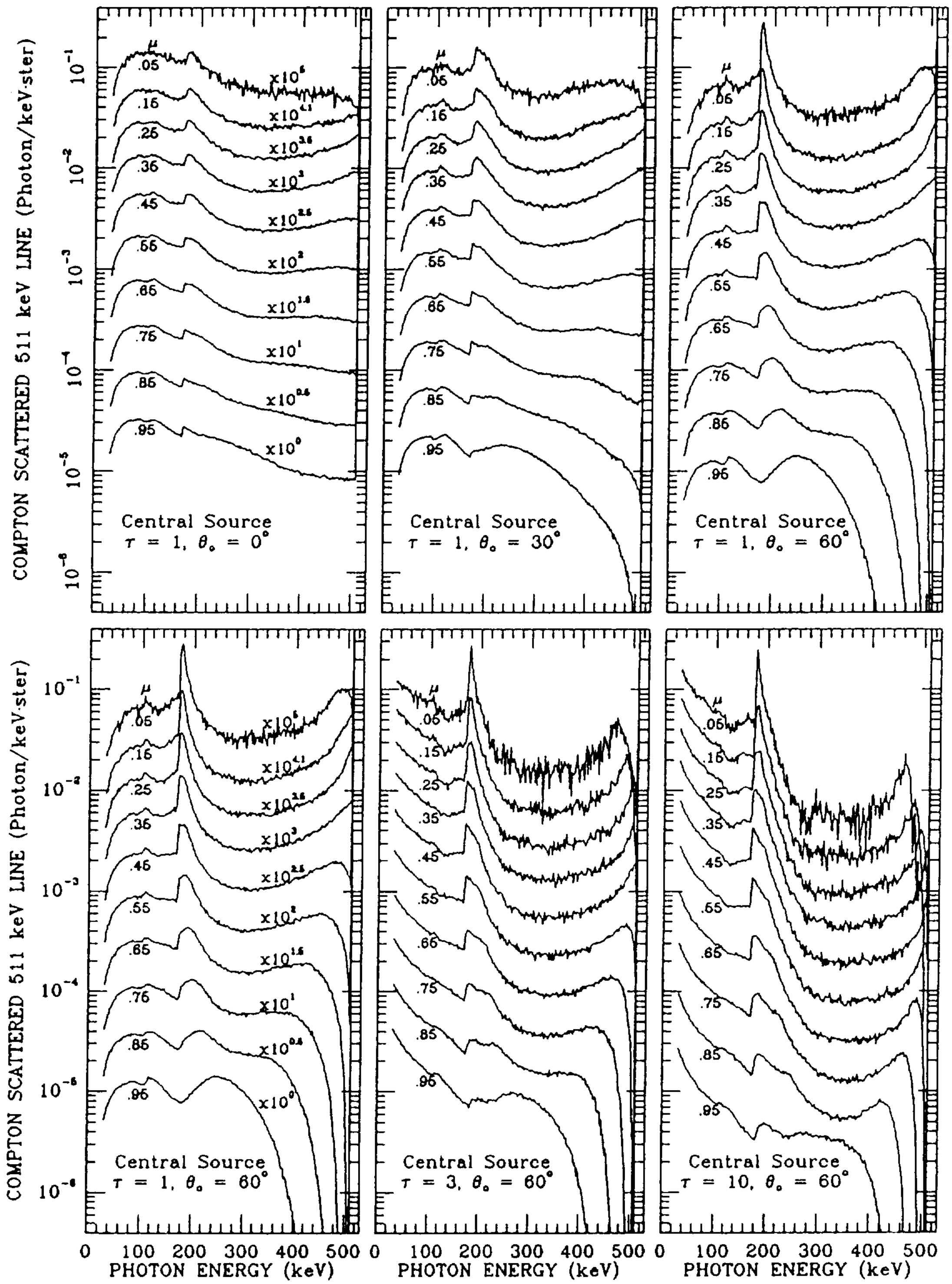

Figure 2. Monte Carlo spectra of the line-like reflection feature at 170 keV and the associated continuum from Compton scattered 511 keV photons in a uniform disk with varying opacities, τ, and central hole opening angles, θ_o, showing the effect of disk opacity and geometry. All of the spectra are normalized to one isotropically emitted 511 keV photon, and individual spectra are displaced from one another by a factor of $10^{0.5}$ or more for clarity.

$$f(\mu) = \frac{1}{2\pi}\exp\left[-\frac{\tau}{2}\left(\frac{1}{\mu} - \frac{\tan\theta_o}{(1-\mu^2)^{1/2}}\right)\right], \text{ for } \theta > \theta_o.$$

The resulting Compton scattered 511 keV line spectra determined for a range of opacities, τ, and opening angles, θ_o, are shown in Figure 2, as a function of μ the cosine of the observing angle. As can be seen, there is a significant singly backscattered line-like feature at 170 keV, or higher energies, in the Compton scattered 511 keV line spectra for each of the disk cases as seen from nearly any angle of observation. The strength, mean energy and shape of this feature all depend on the opacity and the geometry of the disk, i.e. the opening angle of the central hole, and the angle of observation with respect to the disk.

In particular, we see from the upper panels of Figure 2 for large observing angles (small μ), near the plane of the disk, that the 170 keV feature becomes more intense and narrower as the opening angle of the central hole increases. Because the reflecting matter behind the inner edge of the disk subtends a smaller solid angle from the source as the opening angle increases, the scattering angles for observable singly scattered photons are concentrated into a narrower band around 180° and the observable energy band above 170 keV is likewise narrower. Correspondingly at smaller observing angles (larger μ), as θ become less than θ_o, an increasing opening angle concentrates the reflecting matter more nearly perpendicular to the line of sight and there is no reflecting matter directly behind the source. Thus, the peak energy of the reflection feature is shifted up toward 255 keV as scattering angles around 90° dominate the observable singly scattered photon emission, and there is a significant depression in the observable spectrum around 170 keV. This shift in the energy of the peak of the reflection feature can serve as a diagnostic of the observing angle.

Considering the effect of disk opacity, we see from the lower panels of Figure 2, that for large observing angles the 170 keV feature also becomes narrower as the opacity of the disk increases, since that further enhances the singly backscattered photons by attenuating the flux of photons with scattering angles around 90° relative to those around 180°. Because the scattering probability for photons moving away from the observer is already close to unity for large observing angles, increasing the disk opacity can not further increase the peak intensity of the 170 keV feature. For small observing angles, however, increasing the disk opacity does attenuate the flux in the singly scattered feature around 255 keV from scattering around 90°.

In addition to the backscattered feature, we see that at higher energies, just below 511 keV, there is a conspicuous forward scattering peak, which is also a characteristic signature of Compton scattering. As we can see, especially in the lower panels of Figure 2, depending upon the angle of observation, the forward scattered emission does not always extend all the way up to 511 keV. This can happen either because there is no matter close to the line of sight to scatter the line photons, as is the situation for observing angles less than the opening angle of the central hole, or because there is so much scattering matter in the line of sight that the source is completely obscured, as is the situation for large observing angles, closest to the plane of the disk.

We compare these calculated spectra with the observations of the annihilation radiation and accompanying 170 keV line from the direction of the Galactic center.

THE 170 KEV LINE FROM THE GALACTIC CENTER REGION

Positron annihilation radiation in the 511 keV line and in the apparent three-photon orthopositronium continuum has been observed from the direction of the Galactic center since 1970. An analysis of these observations suggests[15] that there are two sources of the emission: a steady, diffuse interstellar source with a broad distribution in galactic longitude, and a variable, compact source, quite possibly an accreting black hole near the Galactic center.

This emission was first measured by Haymes et al.[23] with low resolution NaI spectrometers in a series of three balloon flights in the early 1970s. However, it was not until the fall of 1977 that a narrow (FWHM < 3.2 keV) line was clearly identified at an energy of 510.7±0.5 keV together with an apparent orthopositronium continuum by Leventhal, MacCallum and Stang[1] with a balloon-borne high resolution Ge spectrometer.

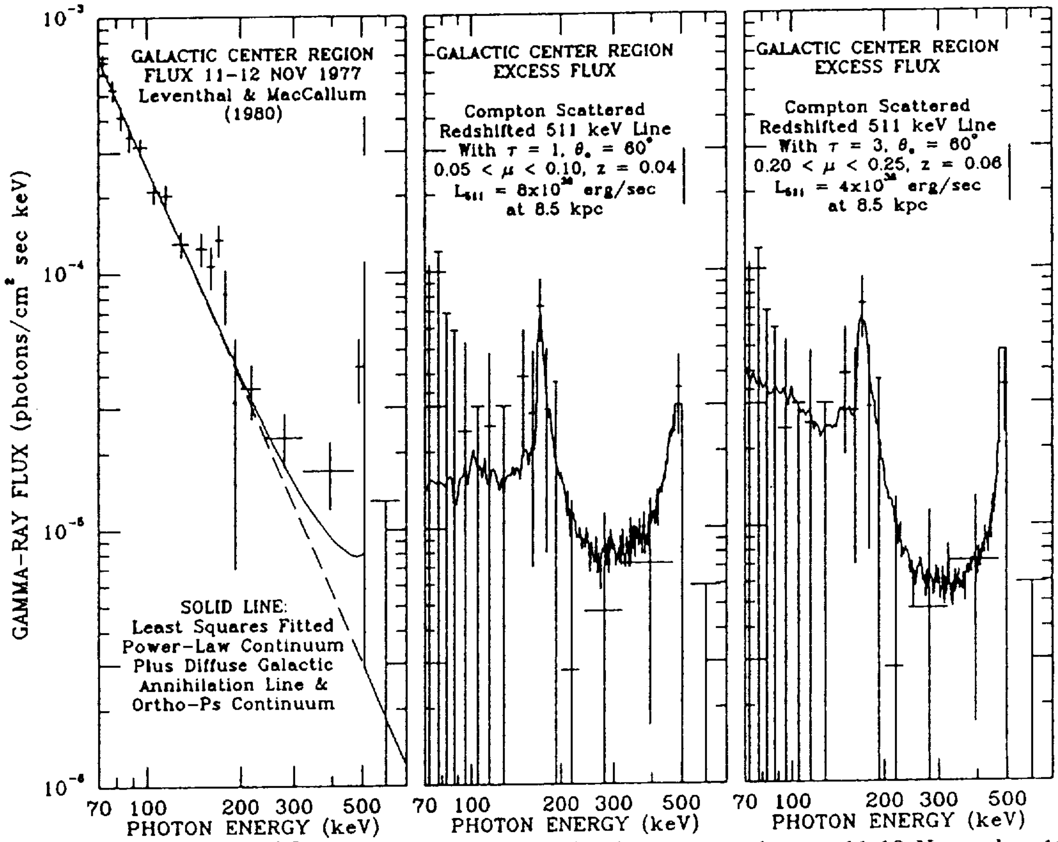

Figure 3. The observed[1,2] spectrum from the Galactic center region on 11-12 November 1977 (left panel), showing the 170 keV and 511 keV lines and other excess flux above a best-fit, low-energy power-law spectrum and the diffuse Galactic annihilation line and orthopositronium continuum flux expected for the detector field of view. This excess flux is also shown separately (central and right panels) with calculated spectra of Compton scattered, slightly-redshifted 511 keV line photons isotropically emitted in a hole of opening angle $\theta_o = 60°$ in a uniform disk. The calculated spectra are for disk opacities τ of 1 and 3, and observing angle cosines μ of 0.05–0.1 and 0.20–0.25, normalized to 511 keV annihilation line luminosities of 8×10^{38} and 4×10^{38} erg s^{-1}, redshifted by 0.04 and 0.06, respectively.

This observation was made during a period < 1977–1979 > when the annihilation line emission from the direction of the Galactic center was significantly higher than average and the variable, compact source was active. It was during this same observation that they[1,2] also detected an unidentified "candidate" line at 170 keV with a width (FWHM) of 12 keV and a flux of $(7.4 \pm 1.8) \times 10^{-4}$ photons cm^{-2} s^{-1} (see Figure 3, left panel). This 170 keV line flux was roughly 60% of that in the narrow 511 keV line, $(1.22 \pm 0.22) \times 10^{-3}$ photons cm^{-2} s^{-1}, seen at the same time. Although the 170 keV line was detected at the 4.1σ or 99.998% confidence level, and no similar negative (presumably spurious) features were found in the spectrum at $> 3.5\sigma$, two other positive unidentified "candidate" lines were also detected at 1611 keV with a width of 10 keV and 3700 keV with a width of 500 keV at 4.9 and 3.9σ, respectively. Lacking a "reasonable identification" of any of these lines, Leventhal and MacCallum[2] cautioned against taking them seriously until they were confirmed by other observations.

We suggested[14] that a reasonable identification of the 170 keV line can be found in Compton backscattering of the 511 keV annihilation line. Moreover, there is now at least one confirming observation of such a line in spectra of the Galactic center region. Matteson et al.[3] observed a line-like feature at 170 keV at the several σ level of significance with a high resolution Ge spectrometer during a balloon flight in May of 1989. There are also suggestions of features in the range from 150 to 250 keV in other published[17–19] spectra. Clearly these and the future GRO observations of the Galactic center region should be reexamined for evidence of such a feature.

In order to identify the 170 keV line observed from the direction of the Galactic center as Compton backscattered annihilation radiation, however, it is necessary to assume a small gravitational redshift. Such a redshift should in fact be expected, if the backscattered feature arises from reflection near the inner edge of an accretion disk around a compact object. Moreover, it shows that the 170 keV line could not originate locally from Compton backscattered annihilation radiation in either the instrument or the earth's atmosphere.

The need to assume a redshift for a Compton backscattering identification of the line arises from the fact that a Gaussian fit to the observed[2] line was centered at 170 keV with a uncertainty of < 0.5 keV and a width (FWHM) of 12 keV, whereas the backscattered feature is cut off sharply below 170.3 keV and such a width would require the effective center of the feature to be shifted higher in energy by $\sim$ FWMH/2, or $\sim$ 6 keV. Thus, if the observed 170 keV line is Compton backscattered 511 keV line emission, the Compton spectrum and the annihilation line must be redshifted by that amount, which would correspond to a $z \sim 6/170 \sim 0.04$. Such a redshift can be produced gravitationally, if the source of the annihilation radiation is located at a distance of $\sim$ 12 Schwarzschild radii from a compact object, which would be consistent with emission and reflection near the inner edge of an accretion disk. This, of course, requires that any observable 511 keV annihilation line photons, coming directly from the source, would be redshifted down by $\sim$ 18 keV to an energy of $\sim$ 493 keV.

Thus, the observed narrow 511 keV line could not be the source of the backscattered photons, but as was previously pointed out[16,20] these photons could not have come from positron annihilation directly in the compact source. That is because the line center of 510.7 ± 0.5 keV determined by Leventhal, MacCallum and Stang[1] only allowed a redshift of < 1.3 keV from the rest energy of 510.9991 keV at the 2σ level, and the subsequent measurement by Riegler et al.[21] in 1979 reduced that to < 0.6 keV. Therefore, even if the diffuse Galactic contribution to the observed line were centered exactly at the rest energy, the annihilation region in which the variable component of the narrow line originates could not be closer than $\sim$ 300 Schwarzschild radii from the compact object. Moreover, if the annihilation region is in a surrounding accretion disk, the observed[1,2] line width, FWHM < 3.2 keV, would not allow it to be closer than $\sim 10^5$ Schwarzschild radii from the compact object, because of Doppler broadening by the Keplerian velocities.

A redshifted annihilation line from the compact source at an energy of $\sim$ 493 keV would lie right in the middle of the data bin just below the 511 keV line in the spectrum of Leventhal, MacCallum and Stang[1,2], shown in Figure 3. The flux of $(1.4 \pm 0.4) \times 10^{-3}$ photons cm^{-2} s^{-1} in this band from 476 to 509 keV is actually larger than that in the narrow 511 keV line and it seems to be quite anomalous, as we shall discuss further below. This flux is also roughly twice that in the 170 keV feature. Such emission may also have contributed to the redshift of the annihilation line observed by Haymes et al.[17] in their first two observations with a low resolution spectrometer.

As can be seen in the left panel of Figure 3, there is a strong power-law continuum underlying all of these features. However, the contribution of the variable source of annihilating positrons to this hard x-ray and gamma-ray continuum is not known, because there are also several highly variable hard x-ray sources[22-23] within the 15° instrumental field of view. But, since we are interested in the non-power-law components of the spectrum, we can simply subtract a best-fit power-law from the observed spectrum. We find that the least squares fit to the spectrum below 135 keV is a power law of $(2.6 \pm 0.1) \times 10^{-4}(E/100\mathrm{keV})^{-2.8\pm0.2}$ photons cm^{-2} s^{-1} keV^{-1}. To this power-law continuum, we also add the diffuse galactic 511 keV line and orthopositronium continuum fluxes expected for the instrumental field of view of 15°, assuming a diffuse galactic 511 keV line flux of $(1.5 \pm 0.3) \times 10^{-3}$ photons cm^{-2} s^{-1} per radian of galactic longitude[15,24-25] and a diffuse galactic positronium annihilation fraction[26] of $0.89^{+0.10}_{-0.06}$.

Comparing the observed flux from the Galactic center region with the sum of the low energy power-law continuum and the diffuse galactic annihilation radiation, we clearly see that there is a significant excess flux not only around 170 keV and in the narrow 511 keV line already noted by Leventhal and MacCallum[2], but also in that seemingly anomalous energy band from 476 to 509 keV, which we suggest includes both redshifted 511 keV line and forward scattered photons from the compact source. The 33 keV width of this data band limits the thermal broadening of the redshifted 511 keV line to a temperature of $< 1.6 \times 10^{7}$ K, assuming direct annihilation with hot electrons[27].

The excess flux alone is shown in the central and right panels of Figure 3, with the additional uncertainties in both the low energy power-law and the diffuse annihilation radiation included in the error bars. Comparing this excess flux with the calculated Compton scattered 511 keV line spectra from the simple accretion disk model discussed above, we see that such emission can in fact account not just for the 170 keV line-like feature, but for all of the rest of the excess flux, as well. Although we do not attempt to explore the full range of possible spectral fitting here, because that is beyond the scope of this paper, these two examples clearly show that Compton scattered 511 keV line emission can in fact give a good fit to the observations. They also allow us to explore some of the constraints on the disk opacity, opening angle and viewing angle that can be set by the observations, and they give a measure of the gravitational redshift and 511 keV line luminosity that are required to fit the observations. We plan much more detailed studies of the observations with more realistic accretion disk models.

SUMMARY

We have shown that Compton scattering of 511 keV electron-positron annihilation radiation produces a line-like reflection feature at $\sim$ 170 keV from backscattered photons. We have further shown that such Compton backscattering of slightly redshifted annihilation line emission from the inner edge of an accretion disk can account for the 170 keV line emission and higher energy continuum observed[1,2] together with the 511 keV annihilation radiation from the direction of the Galactic center. Although the identification of the observed 170 keV line as Compton backscattered annihilation radiation requires a small redshift of 0.04 to 0.06, such a redshift should in fact be expected, if the backscattered feature arises from reflection near the inner edge of an accretion disk around a compact object. Moreover, such a redshift shows that the 170 keV line could not originate locally from Compton backscattering of annihilation radiation in either the instrument or the earth's atmosphere.

Identification of the 170 keV line as Compton backscattered 511 keV line emission provides direct new evidence for an accreting compact source in the direction of the Galactic center, because the diffuse Galactic line emission could not generate such a reflection feature at the observed intensity.

As this example clearly suggests, study of these features in existing spectra and in forthcoming GRO observation of these and other sources can provide unique new diagnostics of the innermost regions of accretion disks around compact objects. Moreover, line-like reflection features from Compton backscattering of other nuclear line emission as well, could also be an important new tool for studying high energy processes in many other astrophysical sources.

Acknowledgements. We thank NASA for financial support under grant NAGW 1970 and the Province of Ontario for support at ISTS. The calculations were carried out on a SUN at ISTS and a VAX at UCSD.

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