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Time lag between hard and soft X-ray photons in QPO sources

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Summary. We show that the delay (of the order of ms) between the quasi-periodic oscillations (QPO), observed from Cyg X-2 and GX 5-1, in a high-energy and a low-energy photon pass-band, can be the result of Compton scattering of photons in a cloud of hot electron gas. This delay depends on the optical depth, electron temperature, and radius of the cloud, and on the spectrum of the input photons. Using Monte Carlo simulations we show how, for an assumed input spectrum of photons, the observed delay and X-ray spectrum can be used to constrain the size of the scattering cloud.

We find that, in addition to scattering of an oscillating signal in a constant cloud, scattering of a constant source of input photons through a cloud with oscillating optical depth can also give rise to both QPO in the emergent photons, and a time lag between high-energy and low-energy photons.

1 Introduction

From a cross-correlation of high-time resolution *EXOSAT* data of the QPO source Cyg X-2, obtained in two photon energy bands, Hasinger (1986) found that the 'hard' photons lagged the 'soft' photons. The delay, which varies between ~1 and ~4 ms, is anti-correlated with the QPO frequency. GX 5-1 also showed such a 'hard' photon time lag, by ⩽1 ms (van der Klis 1986). The complex cross-spectra of these sources showed that the lag is caused by intensity variations at the QPO frequency (van der Klis *et al.* 1987b).

Hasinger (1986) suggested that the delay is due to Compton (up-) scattering of photons in a cloud of hot electron gas in the vicinity of the neutron star. High-energy photons have, on average, undergone more scatterings than low-energy photons; they have therefore travelled a longer distance through the cloud, i.e. they are delayed.

We present here some results of exploratory calculations of the expected time delay of photons in different energy bands, based on Monte Carlo simulations of Compton scattering in a spherical cloud of hot electron gas. We show that the delay may be understood both by (i) Comptonization of an oscillating signal in a steady cloud, as well as (ii) Comptonization of a constant signal in a cloud of oscillating optical depth. In the latter case the QPO themselves are the result of the variable optical depth.

2 Method

We suppose that the observed X-rays originate from the centre of a spherical, homogeneous cloud of electrons (with radius R_c). The average time, t_{ssc}, for photons to escape from the cloud depends on the number of scatterings, i.e. on the optical depth, τ, of the cloud. For Compton scattering $t_{esc}=\tau R_c/2c$ (Syunyaev & Titarchuk 1980). Since this is an average value for all photons it cannot be compared to the time lag, observed in Cyg X-2 and GX 5-1, which corresponds to the difference in escape times for photons in two energy bands.

To find this difference the following problem must be solved. Given the initial energy (E_i) of a photon emitted by the central point source, the optical depth (τ), and radius (R_c) of the cloud, the temperature (T_e) of the electron gas, and the energy (E_f) of the emergent photon, what is the probability distribution of the escape time of the photon? For large optical depths and $E_i \ll kT_e$ this problem can be solved analytically (Payne 1980; Pozdnyakov, Sobol & Syunyaev 1983).

The delay observed in Cyg X-2 and GX 5-1 refers to photons in two wide energy bands, and also the energy range of input photons can be very wide. When τ is of order unity, or the condition $E_i \ll kT_e$ does not hold, an analytic expression for the delay cannot be easily found.

We therefore made Monte Carlo simulations of the scattering process, using a computer code based on the methods of Pozdnyakov *et al.* (1983). For an assumed energy distribution of input photons, and values for kT_e, τ and R_c, the code generates the distributions in energy and time of the emergent photons. From a cross-correlation of the time distributions of photons in two given energy bands the delay can be inferred (here we have not included the detector response and interstellar absorption, which changes the weighting in the averages over the two energy bands).

We modelled two physically different situations. In some QPO models (e.g. accretion-modulated beat-frequency models, *cf.* Lamb *et al.* 1985; Berman & Stollman 1986) the QPO are thought to originate before the scattering of the photons occurs. We treated this by assuming that the number of input photons varies in time as $N(t)=N_0(1+\cos 2\pi\nu t)$, where ν is the QPO frequency (taken to be 30 Hz).

In the obscuration model of van der Klis (1986) the QPO are due to an oscillation of the optical depth of a scattering medium. We will not model the geometry of this medium in any detail, but address the question whether a constant input intensity of photons, combined with a changing optical depth, can give rise to an oscillating output signal, and a time lag between photons in different energy bands. Therefore, we use a spherically symmetric cloud of electrons, with fixed R_c, and change the optical depth according to $\tau(t)=\tau_0+\tau_1\cos 2\pi\nu t$.

The delay between photons in different energy bands depends not only on the parameters of the cloud, but also on the spectrum of the input photons.

X-ray spectra of bright bulge sources can be well described by the sum of two or more simple spectral functions. Some of these models are particularly relevant here in that they contain a Comptonized component with either very soft photons (White *et al.* 1986) or a ~1 keV blackbody (Hirano *et al.* 1984), as input photons.

Since, in addition to the observed delays, we wish our model to produce X-ray spectra conforming to either of these two spectral models, we have used both very soft photons (10 eV), and a 1 keV blackbody as input in our simulations. As the shape of the emergent X-ray spectrum depends on the input energy distribution, and on τ and kT_e, the observed delay can be used to constrain the size of the cloud.

3 Results

3.1 COMPTONIZATION OF LOW-ENERGY PHOTONS ON HOT ELECTRON GAS

The spectral shape of the Comptonized component depends on T_e and τ, but not on the initial photon energy, as long as $h\nu \ll kT_e$. In order to constrain τ and kT_e we used the average X-ray spectrum of GX 5-1, as observed when this source shows QPO (van der Klis *et al.* 1987a). Fig. 1 shows the ($\tau - kT_e$) relation for which the calculated, Comptonized spectrum gave reasonable fits to the observed spectrum.

With a sinusoidally varying input intensity of soft photons, we find that for the parameters, as presented in Fig. 1, the time distribution (averaged over the energy band) of the (1.2–5.8 keV) photons is delayed with respect to the (5.8–16 keV) photons. The delay (found by a cross-correlation of these time distributions), is plotted in Fig. 2 as a function of the optical depth of the scattering cloud.

For GX 5-1 the observed delay is ~0.5 ms (van der Klis *et al.* 1987b). From Fig. 2 this would imply that the radius of the cloud is smaller than 10^7 cm. The delay found in Cyg X-2 is several ms (Hasinger 1986; van der Klis *et al.* 1987b), which would imply a radius of several times 10^7 cm.

3.2 COMPTONIZATION OF A 'HARD' (~1 keV) BLACKBODY SPECTRUM

The parameters that determine the Comptonized blackbody component are the blackbody temperature kT_b of the input photons, τ and kT_e. We have compared the high-energy tails (i.e. $E \geq 10$ keV) of the calculated spectra with the observed spectrum of GX 5-1, and find reasonable fits for τ in the range 2–4, kT_e between 15 and 8 keV, and kT_b in the range 1.2–1.4 keV.

Again a delay was found between photons in the hard and soft energy bands. No simple relation

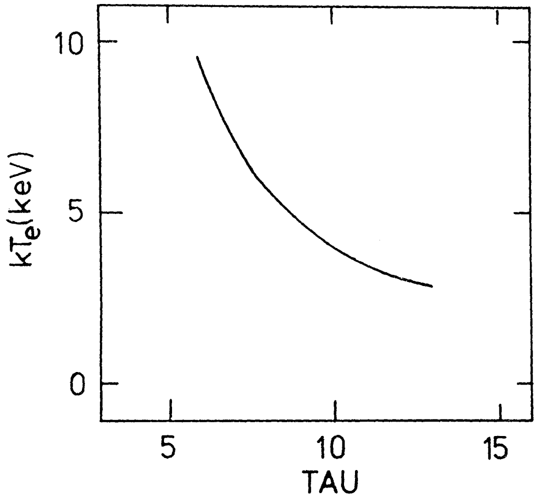

Figure 1. The curve in the ($\tau - kT_e$)-plane for which the calculated, Comptonized spectra give reasonable fits to the observed spectrum of GX 5-1. In these calculations it was assumed that the input photons have energies much less than kT_e.

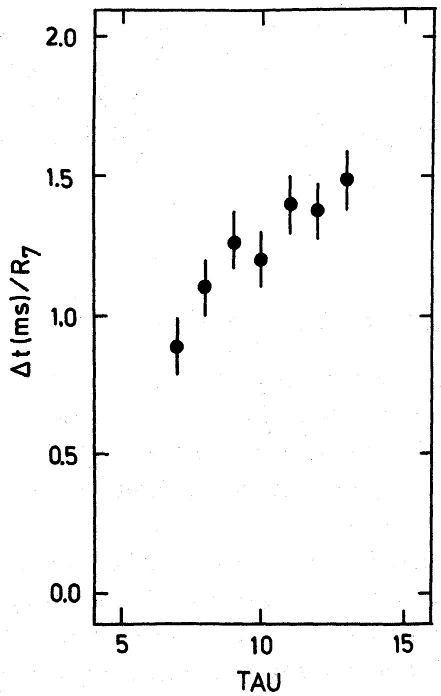

Figure 2. The calculated time delay as a function of optical depth, for the case of a constant cloud of electrons, and a sinusoidally varying input of photons with energies much less than kT_e. R_7 is a (dimensionless) radius of the scattering cloud ($R_7=R/10^7$ cm).

could be found between this delay and the parameters kT_b, kT_e, τ and R_c. In the ranges quoted above for these parameters the time delay is approximately given by $\Delta t \sim (0.1\text{–}0.3)\,R_7$ ms where R_7 is R_c in units of 10^7 cm.

In the case of GX 5-1 this implies a radius of the scattering cloud of a few times 10^7 cm, while for Cyg X-2 the radius is more than 10^8 cm.

3.3 VARIABLE OPTICAL DEPTH

In simulating the case of a constant input signal, and a varying optical depth, we used as parameters $R_c=4\times10^7$ cm, $kT_e=4$ keV, and assumed a 10 eV blackbody input spectrum. The optical depth is assumed to vary as $\tau(t)=2\cos(2\pi\nu t)+9$, with $\nu=30$ Hz. The average X-ray spectrum, obtained by integrating the emergent photon energy distribution over one cycle of optical depth variation, does not differ significantly from that for a constant optical depth ($\tau=9$), all other input parameters taken equal.

The time profiles of the emergent photons in the (1.2–5.8 keV) and the (5.8–16 keV) bands are shown in Fig. 3. From this figure it appears that:

(i) Compton scattering of a constant input signal through a cloud of oscillating optical depth can lead to oscillations in the emergent X-rays. These are mainly the result of a variation of the total number of photons locked in the cloud, which acts as a varying buffer.

(ii) The signal in the high-energy band is delayed with respect to that in the low-energy band. This delay is again due to the fact that at each instant higher energy photons, on average, have undergone more scatterings than lower-energy photons.

The amplitude of the signal in the high-energy band is larger than that in the low-energy band. This is probably due to the fact that photons can only reach the high-energy band if the optical

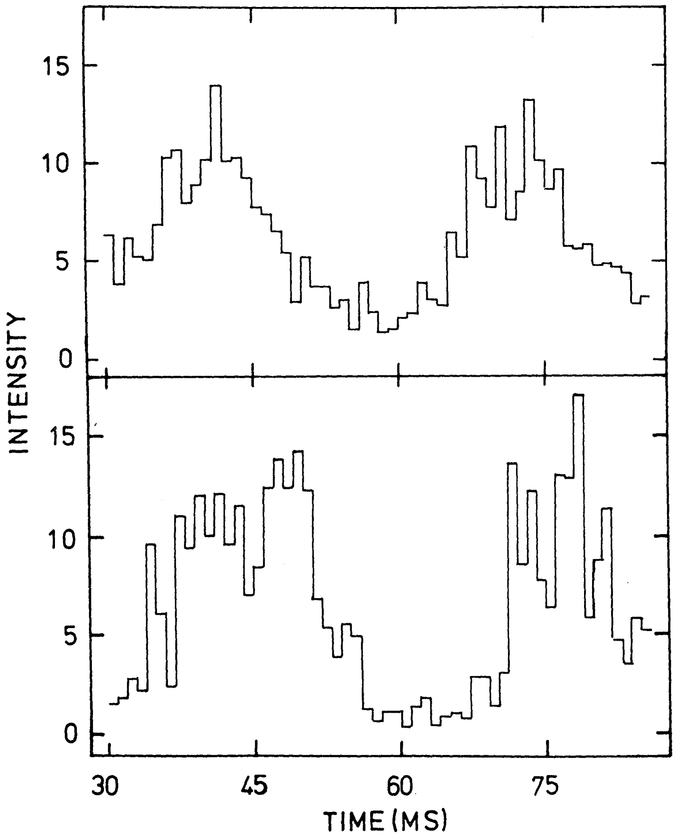

Figure 3. The time profiles of photons in a low-energy band (1.2–5.8 keV; top panel) and a high-energy band (5.8–16 keV; bottom panel) after scattering of a constant input signal of photons on electrons in a cloud of varying optical depth.

depth (i.e. the average number of scatterings) is large enough. Although it is premature to consider this as support for this particular QPO mechanism, it is of interest to note that this fits the observed increase with photon energy of the rms variation of the QPO in Cyg X-2 (Hasinger 1986), GX 5-1 (van der Klis 1986) and Sco X-1 (Priedhorsky *et al.* 1986).

4 Discussion and conclusion

The delay of hard photons with respect to soft ones as observed in GX 5-1 and Cyg X-2, as well as their X-ray spectra, can be explained as a result of Comptonization. Both an oscillating intensity of input photons, and an oscillating optical depth (combined with a constant input intensity of the photons) can explain the QPO phenomenon and the observed delay. The latter phenomenon can, therefore, not be easily used to distinguish between QPO models that are either based on an oscillating photon source, or on an oscillating obscuration of a constant source.

Within the framework of these models the anti-correlation between the time lag and QPO frequency observed in Cyg X-2 (Hasinger 1986) implies that the properties of the scattering cloud change as the QPO frequency changes. If this frequency is a measure of a radial distance from the neutron star (basically Kepler's third law) this anti-correlation might arise naturally if the size of the cloud is related to this distance (Hasinger 1986).

The characteristics of the scattering medium can in principle be inferred from the observed X-ray spectrum and the time delay. However, the origin of the spectra is still uncertain, and we have used two different models of the spectra of bright bulge sources. In the model of White *et al.*

(1986) the strongest component in the spectrum is due to Comptonization of low-energy photons on high-energy electrons. This Comptonized component contains more energy than the second (blackbody) component (thought to originate from the neutron star surface). The question then arises as to why most of the accretion energy does not originate at the neutron star surface, but is in the form of kinetic or thermal energy of electrons in the scattering medium.

In the spectral model of Hirano *et al.* (1984) this problem does not exist as most of the energy is liberated at the neutron star surface. In this case the observed delay, especially for Cyg X-2, implies a very large electron cloud.

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