Detection of an X-ray periodicity in the Seyfert galaxy IRAS 18325–5926

K. Iwasawa¹, A.C. Fabian¹, W.N. Brandt², H. Kunieda³, K. Misaki³, C.S. Reynolds⁴ and Y. Terashima³

¹ Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
² Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park PA 16802, USA
³ Department of Astrophysics, Nagoya University, Chikusa-ku, Nagoya 464-01, Japan
⁴ JILA, University of Colorado, Campus Box 440, Boulder CO 80309-0440, USA

ABSTRACT

We report the detection of a 5.8 × 10⁴ s periodicity in the 0.5–10 keV X-ray light curve of the Seyfert galaxy IRAS18325–5926, obtained from a 5-day ASCA observation. Nearly 9 cycles of the periodic variation are seen; it shows no strong energy dependence and has an amplitude of about 15 per cent. Unlike most other well-studied Seyfert galaxies, there is no evidence for strong power-law red noise in the X-ray power spectrum of IRAS18325–5926. Scaling from the QPOs found in Galactic black hole candidates suggests that the mass of the black hole in IRAS18325–5926 is ∼ 6 × 10⁶–4 × 10⁷ M⊙.

Key words: galaxies: individual: IRAS 18325–5926 – galaxies: Seyfert – X-rays: galaxies

1 INTRODUCTION

ASCA X-ray spectra of many Seyfert galaxies show that the iron emission line is broad and skewed to low energies (Tanaka et al 1995; Nandra et al 1997), indicating that the X-rays originate from above the surface of an accretion disk close to a massive black hole (Fabian et al 1995). The line profiles demonstrate that much of the X-ray emission originates from about 10–20 gravitational radii, but do not constrain the mass of the black hole. For that the emission radius is required in physical units.

X-ray variability is an important characteristic of such active galactic nuclei (AGN) and may hold the key to obtaining that size. Short time scale X-ray variations are probably due to individual flares above the accretion disk and so do not determine the orbital radius unless the flare mechanism is understood much more than is currently the case. A periodic signal would suffice if the origin of the period, orbital or otherwise, was known.

Previous studies of X-ray variability of AGNs have found that power spectra are featureless and power-law in shape (e.g., Lawrence et al 1987; McHardy 1989). No characteristic periodicity has been found except for possible quasi-periodic oscillations (QPOs) in NGC5548 (~ 500 s, Papadakis & Lawrence 1993; Tagliaferri et al 1996 argue against the presence of QPO in those data), NGC4051 (~ 1 hr, Papadakis & Lawrence 1995) and RXJ0437.4–4711 (0.906 ± 0.018 dy, Halpern & Marshall 1996). Very clear QPO have been seen in several Galactic Black Hole Candidates; a 67 Hz QPO in GRS 1915+105 (Morgan, Remillard & Greiner 1997) and QPO at lower frequencies, 1–10 Hz, in GX339-4 and GS 1124–68 (Dotani 1992; Belloni et al 1997). Here we report the discovery of a periodic signal from IRAS18325–5926, which is a Seyfert galaxy with a broad iron line (Iwasawa et al 1995, 1996a). The X-ray source is one of the complete X-ray sample selected by the HEAO-1 A2 survey (Piccinotti et al 1982) and it was identified with the IRAS galaxy (= Fairall 49) by Ward et al (1988). Although its narrow-emission-line-dominated optical spectrum is similar to that of Seyfert 2 galaxies (DeGrijp et al 1985), the presence of a weak broad wing to the Balmer lines (Carter et al 1984; Iwasawa et al 1995) suggests a dust-obscured broad-line region in this galaxy. The X-ray spectrum is moderately absorbed by a column density of ~ 1 × 10²² cm⁻², which is consistent with the picture of an obscured Seyfert 1 nucleus. Apart from the slightly steep continuum slope (Γ ∼ 2.1), the absorption-free hard X-ray emission (> 2 keV) has similar properties to those of Seyfert 1 galaxies. The X-ray source has been found to be highly variable, as observed in other Seyfert 1 galaxies such as MCG–6-30-15.

A five-day long ASCA observation with a net exposure time of ~ 200 ks has been carried out with the aim of investigating X-ray variability in the source, including the iron line and underlying continuum. The general spectral properties of the X-ray source are similar to those seen before, and will be discussed in another paper. We report in this Letter on a timing analysis of the ASCA data.
2 THE ASCA DATA

IRAS18325–5926 was observed with ASCA for 5 days between 1997 March 27 and 1997 March 31. The X-ray telescopes pointed at the source at the 1CCD mode nominal position. Averaged count rates detected with the four detectors over the total observing run are shown in Table 1. The Solid state Imaging Spectrometers (SIS; S0 and S1) are operated with the Faint mode using one standard CCD chip in each detector. The standard settings of PH mode were used for the Gas Imaging Spectrometers (GIS; G2 and G3). The data reduction was performed using FTOOLS (version 4.0) and standard calibration. After data selection, the net exposure times of useful data are 204 ks for the SIS and 180 ks for the GIS.

The source events were collected from a circular region centred on the source with a radius of 4 arcmin for the SIS and 6 arcmin for the GIS. Background in each detector was taken from a source-free region on the same detector. The backgrounds were basically stable with an intensity about 7–8 per cent of the mean counts collected from the source regions.

The mean X-ray flux of the source is $1.7 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the 2–10 keV band during the observation, a factor of $\sim 2$ brighter than the previous ASCA observation in 1993 but a factor of $\sim 1.5$ fainter than the Ginga observation in 1989. The absorption-corrected 2–10 keV luminosity is $L_{2-10keV} \sim 3 \times 10^{41}$ erg s$^{-1}$ ($H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$).

The minimum time resolution of the data is 4 s. X-ray light curves from the four detectors have been binned into 360 s for each data point for the timing analysis presented below. The count rate decreased gradually over the whole observation with many flares on short timescales (Fig. 1). The light curve appears to have a characteristic time scale of $\sim 6 \times 10^4$ s as well as random shorter timescales. We have searched for a possible periodicity of the X-ray modulation and examined its significance using a periodogram technique.

3 TIMING ANALYSIS

The Lomb algorithm (Lomb 1976) is appropriate for searching for a periodic modulation from unevenly sampled data such as inherent in observations from low orbit satellites like ASCA (Tanaka, Inoue & Holt 1994). In Fig. 2, the power-spectrum computed using the Lomb periodogram (Press et al 1992) is shown.

A large peak with a period just longer than the dataset and due to the trend seen across the light curve, lies at the lowest frequency shown in Fig. 2. There are two other

![Figure 1. The ASCA S0 light curve in the 0.5–10 keV band. Each data bin is of exposure time 1000 s for clarity while the timing analysis used 360 s bins. The epoch of the start is 1997 March 27, 13:21:31 (UT). The nine stars plotted at the top are spaced at the detected frequency.](image-url)
significant peaks. The higher frequency peak at $1.72 \times 10^{-4}$ Hz or 96.9 min is likely to originate in the orbital period of ASCA (Tanaka et al 1994). Another, more significant, one is found at $1.725 \times 10^{-5}$ Hz, corresponding to a period of 58.0 ks. This peak is found strongly in all detectors (Table 2) except for G2 in which the observed count rate is the lowest among the four detectors. The frequencies of the peak being random are shown in Table 2. If there is significant clumping in the data sampling, then the derivation of the probability could be affected (Horne & Baliunas 1986). We have verified that this is not the case using simulated light curves, one in which random count-rates (with the same mean and variance as the data) are assigned to the observed times and the other in which the count rates were shuffled.

The periodicity is confirmed with an epoch-folding technique. The 90 per cent statistical error to the 58.0 ks peak for the observed data in the $\chi^2$–(trial period) diagram, when it is fitted with a gaussian, is $\sim 0.3$ ks. The systematic error in deriving a coherent periodicity is found to be $\sim 0.2$ ks, applying the same technique to simulated sine waves with a period of 58.0 ks, holding the same time locations and similar mean count-rate and amplitude to the real observation. Thus the error of the period is estimated to be $\sim 0.4$ ks.

The folded light curve at the detected period is shown in Fig. 3. The modulation is arch or sinusoidal in shape with an amplitude of $\sim 15$ per cent. There is no strong evidence for X-ray colour variation associated with the periodicity. We note that the power spectra of the variability of Seyfert galaxies is typically power-law in shape over the frequency intervals shown in Fig. 2 (McHardy 1989). The possibility of such red noise complicates the true assignment of significance to the peak in Fig. 2. The probabilities in Table 2 are strictly for a sinusoidal signal in white noise. Apart from a large peak at the lowest frequencies due to the trend in the lightcurve, we do however see no evidence for red noise. Over the frequency range $3 \times 10^{-6}$ Hz to above $10^{-4}$ Hz, the peaks in the power spectrum are similar to those expected from white noise, apart from the spike at $1.73 \times 10^{-5}$ Hz. If it is argued that the spike is due to red noise, then we must ask why there are no similar large peaks at $10^{-5}$ Hz and below. We find that the power spectrum (and lightcurve) are not at all similar in shape to simulations made with red noise. (The light curve of MCG–6-30-15 from the previous ASCA long look ($\sim 4$ dy, Yaqoob et al 1997) does show red-noise.)

We made 1000 simulated lightcurves with the observed time sequence and (phase) randomized $f^{-1}$ noise, normalized to give the same variance as the real dataset. The minimum power (in the same units as Fig. 2) in the frequency range from $3 \times 10^{-6}$ Hz to $1.5 \times 10^{-4}$ Hz was 42, decreasing to 25 when the lower frequency was $4 \times 10^{-6}$ Hz. If the power varies as $f^{-1.5}$, which is more typical of AGN, then

### Table 2. Results of the Lomb periodogram analysis. Probabilities that the signals could occur randomly from the four detectors are shown for the peak at $1.725 \times 10^{-5}$ Hz. G2 (which had the lowest count rate from the source) has a more significant peak at a frequency $1.27 \times 10^{-3}$ Hz, not seen in the other detectors.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>$1 \times 10^{-10}$</td>
</tr>
<tr>
<td>S1</td>
<td>$9 \times 10^{-9}$</td>
</tr>
<tr>
<td>G2</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>G3</td>
<td>$3 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

Figure 2. The power spectrum derived from the ASCA S0 light curve of IRAS18325–5926 in the 0.5–10 keV band. A peak at the right corresponds to the ASCA orbital period. The highest peak at $1.725 \times 10^{-5}$ Hz is intrinsic to the source. Large power at the low frequency below $3 \times 10^{-6}$ Hz is due to the decreasing trend across the whole observation. Note that a frequency corresponding to the whole observation length is $\sim 2 \times 10^{-6}$ Hz.

Figure 3. The ASCA S0 light curve folded at the detected period. Two cycles are shown for clarity. The original data (dotted line) are averaged into 10 bins per cycle (thick solid line). Error bars to count rates are calculated from the square root of the number of counts integrated over each bin while the standard deviation in each bin is typically $\sim 0.12$ ct s$^{-1}$. The folded light curve at the detected period is shown in Fig. 3. The modulation is arch or sinusoidal in shape with an amplitude of $\sim 15$ per cent. There is no strong evidence for X-ray colour variation associated with the periodicity.
these values rise to 80 and 60 respectively. All of these far exceed the power seen in that frequency range in the real dataset. If the $f^{-1}$ power is scaled down to match the observations then the maximum power seen in the simulation beyond $1.5 \times 10^{-5}$ is less than 10. We conclude that the observations are inconsistent with any simple power-law red noise model.

The peak at $1.725 \times 10^{-5}$ Hz is nearly 10 times the frequency of the peak due to the ASCA orbital period. We consider this to be a chance coincidence. To the best of our knowledge, there is no corresponding frequency originating in the spacecraft. This has been checked using the light curves of the calibration source of the two GIS detectors during the present observation and the light curve of two-day long ASCA observation of a stable X-ray source, the Centaurus cluster, kindly provided by S. Allen. An examination of the X-ray image rules out a possibility that wobbles of the spacecraft causes the observed X-ray modulation.

Note that the X-ray source is the brightest both in the ASCA and ROSAT PSPC images of the region and is located at the optical position of the galaxy (18°36′58″, −59°24′09″, J2000). Simultaneous ROSAT and ASCA observations of the source in 1993 (Iwasawa et al 1996) show a correlated decrease in flux by a factor of about two, confirming that the ROSAT and ASCA sources are the same. We show in Fig. 4, the ROSAT PSPC image overlaid on the digitized UKSTU optical image. The offset of the X-ray and optical position is $\sim 10$ arcsec, which is within the PSPC positional uncertainty.

To eliminate further any residual doubt that the variability reported here is from IRAS18325–5926, since the period is in the range of that of low-mass X-ray binaries and some cataclysmic variables, we have estimated the probability of a chance alignment with a Galactic object by scaling from the Piccinotti et al (1982) X-ray sample. This implies about 100 Galactic objects in the Sky above $|b| = 20^\circ$ at the flux level of IRAS18325–5926 and thus probabilities of about $3 \times 10^{-6}$ and $10^{-7}$ of a further object in the 1 arcmin and 10 arcsec radius error boxes obtained from the ASCA and ROSAT images, respectively. We note that both images are consistent with a single point source. As mentioned in the Introduction, the observed X-ray absorption is fully consistent with the optical classification of the Seyfert galaxy, but unlikely for a Galactic source. We conclude that it is most unlikely that we are repeating the case of NGC6814, where the X-ray variability detected by non-imaging detectors was due to a cataclysmic variable 40 arcmin from the galaxy (Madejski et al 1993). The IRAS galaxy is by far the most probable X-ray source.

4 DISCUSSION

The periodicity found in the light curve from the long observation is about 58 ks which is probably intrinsic to the source whilst the 97 min peak is due to the ASCA orbital period. A similar X-ray flux variation is apparent in the previous ASCA PV (Iwasawa et al 1996a) and Ginga (Iwasawa et al 1995; Smith & Done 1996) observations. The duration of each of those observations was about one day and so only slightly longer than the period (~16 hr). The data sets are too widely spaced to phase together.

The (Newtonian) orbital period at $5R_g = 10r_{\text{g}}$ is $3.4 \times 10^3 M_8 R_1$ s where the mass is in $10^8 M_\odot$ and the radius is $10R_1 r_{\text{g}}$. So it could easily be occurring at $10 r_{\text{g}}$ for a $1.7 \times 10^8 M_8$ black hole or at $20 r_{\text{g}}$ for a $2.1 \times 10^7 M_8$ one. In other words, a 16 hr period is reasonable for orbital variations at 10–20 gravitational radii in a disk around a black hole of mass $2 \times 10^7 - 10^9 M_8$. The Eddington limit for such masses is above $10^{36}$ erg s$^{-1}$, well above that observed.

What we do not know from the 9 cycles that we have seen is whether the variation is strictly- or quasi-periodic. Further observations are necessary to test whether the observed periodicity is long-term or part of a QPO. The quality factor of the current variation is at least 30 and could be much higher. A strict periodicity will be difficult to explain. The most obvious clock would be an object in orbit about the accreting black hole. The lifetime against spiral-in due to gravitational radiation losses would be only weeks for another black hole of similar mass to the primary (say $10^7 M_8$), increasing as the inverse mass for much smaller objects. A star orbiting within an accretion disk does isolate a particular radius (see discussion by Syer, Clarke & Rees 1991) and could last 100,000 yr but it is not obvious how it could modulate the X-ray emission.

A transient periodicity could be due to a very long-lived flare, or flare patch, on the disk. The appearance of small variation originating at a few Schwarzschild radii may be boosted relativistically by orbital motion (see e.g., Boller et al 1997).

A 67 Hz QPO has recently been discovered with the Rossi X-ray Timing Explorer (RXTE) in the Galactic black hole candidate GRS 1915+105 (Morgan, Remillard & Greiner 1997). If this and the periodicity seen in IRAS18325–5926 are related to the orbital period at the
same radius (in gravitational units) in each system, then the masses of their black holes should scale as $\frac{67}{1} \times 10^{-5}$ which is about 4 million. Assuming that the black hole in GRS 1915+10 is $10 M_\odot$ then we find that the mass of the black hole in IRAS18325–5926 is $\sim 4 \times 10^7 M_\odot$. When not that both GRS 1915+10 and IRAS18325–5926 are observed at moderately high inclinations, of about 70 deg and 50 deg, respectively.

QPO at lower frequencies, 1–10 Hz, have been seen in the Galactic Black Hole candidates GX339-4 and GS 1124–68 (Dotani 1992; Belloni et al 1997). The origin is again unknown, but simple scaling would then indicate a mass of $4 \times 10^6 M_\odot$, dependent on the black hole mass of the Galactic sources. In these cases, the QPO are seen mostly when the source is very luminous, possibly close to the Eddington limit, although they were also seen in GS 1124–68 four months after its peak.

It is unclear why any particular radius is favoured. One possibility is the disk oscillation model proposed by Nowak et al (1997) for GRS 1915+10. General relativistic effects cause the epicyclic frequency for matter in the disk to have a maximum close to, but not at, the inner radius of the disk. This can lead to g-mode oscillations in the disk causing QPO at that frequency. However, as discussed by Nowak et al (1997) the power in such QPO should only be a few per cent of that of the disk emission. It is unlikely that they cause a 10 per cent oscillation of the emission from the corona above the disk.

Perhaps the spin of the black hole is responsible, if its axis is offset from that of the disk. The Bardeen-Petterson effect (1975) due to the dragging of inertial frames close to the black hole then causes the inclination of the disk to change at a radius of some tens of gravitational radii (see Rees 1984). If the inclination of the disk is moderately high then oscillations near that radius may be detectable through obscuration and/or reflection.

Acknowledgements

We thank all the member of the ASCA team. T. Dotani is thanked for helpful discussion. The ROSAT PSPC image was retrieved from the ROSAT archive maintained at the Goddard Space Flight Center. The optical UK Schmidt image was taken from the Digitized Sky Survey produced by Space Telescope Science Institute and the original data were taken by Royal Observatory Edinburgh. ACF and KI thank Royal Society and PPARC, respectively, for support. CSR thanks the National Science Foundation for support under grant AST-9529175.

REFERENCES

Carter D., 1984, Astron. Express, 1, 61

Dotani T., 1992, in Frontiers of X-ray Astronomy, eds Y.
Tanaka, K. Koyama, Universal Academy Press Inc, Tokyo, 151
Fabian A.C., Nandra K., Reynolds C.S., Brandt W.N., Otani C.,
Iwasawa K., Kunieda H., Tawara Y., Awaki H., Koyama K.,
Iwasawa K., Fabian A.C., Mushotzky R.F., Brandt W.N., Awaki H.,
Madejski G.M., Done C., Turner T.J., Mushotzky R.F.,
Serlemitsos P., Fiore F., Sikora M., Begelman M.C., 1993,
Nat, 354, 626
McHardy I.M., 1989, in Proc 23rd ESLAB Symposium (ESA
SP-296, Paris, ESA), 2, 1111
Mushotzky R.F., Done C., Pounds K.A., ARAA, 31, 717
Nandra K., George I.M., Mushotzky R.F., Turner T.J., Yaqoob T.,
Nowak M., Wagner R.V., Begelman M.C., Lehr D.A., 1997,
Papadakis I.E., Lawrence A., 1993, Nat, 361, 233
Piconetti G., Mushotzky R.F., Boldt E.A., Holt S.S., Marshall F.E.,
Press W.H., Teukolsky S.A., Vetterling W.T., Flannery B.R.,
Rees M.J., 1984, ARAA, 22, 471
Tagliaferri G., Bao G., Israel G.L., Stella L., Treves A., 1996,
Tanaka Y. et al 1996, Nat, 375, 659
Ward M.J., Done C., Fabian A.C., Tennant A.F., Shafer R.A.,
324, 767
Yaqoob T., McKernan B., Ptak A., Nandra K., Serlemitsos P.J.,