Infrared synchrotron oscillations in GRS 1915+105

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ABSTRACT

We report simultaneous observations of the black hole candidate X-ray transient GRS 1915+105 in the infrared at K and in the radio at 2 cm. Oscillations of period 26 min were observed in both wavebands, having (dereddened) peak–peak amplitudes of about 40 mJy and with the IR leading the radio by 7 min, or perhaps by 33 or 59 min. A synchrotron origin for the oscillations continues to seem very likely. We consider a range of problems raised by these observations, and briefly discuss the applicability of expanding-synchrotron source or conical jet models to the oscillations. Comparing simplistic estimates of the ejecta mass to the missing inner disc mass in the model of Belloni et al., we find that a significant fraction of the inner disc may be ejected during the oscillations.

Key words: binaries: close – stars: individual: GRS 1915+105 – infrared: stars – radio continuum: stars

1 INTRODUCTION

GRS 1915+105 is a highly unusual, extremely bright and variable black hole candidate. Discovered as an X-ray source in 1992 (Castro-Tirado et al. 1992) it has remained more or less detectable (although with an extreme range of variability) for the past five years. Shortly after its discovery, Mirabel & Rodríguez (1994) made observations of the radio counterpart with the VLA and discovered jet-like outflows with apparent superluminal motions corresponding to true bulk velocities of \(\sim 0.9c\). As well as long-term variability, the source exhibits a wide range of phenomena on timescales from milliseconds upwards, which may hold the key to the nature of the accretion flow around the black hole. In particular, multiwavelength oscillations with with periods 1–60 minutes have been the subject of much discussion, as summarised below.

1.1 Oscillations from GRS 1915+105

Pooley (1995, 1996) reported the discovery of quasi-periodic radio oscillations, with periods in the range 25 – 40 min, from GRS 1915+105 in radio observations at 15 GHz. Pooley & Fender (1997), hereafter PF97, reported over 18 months’ of radio monitoring, including many epochs of such radio QPO with periods in the range 20 - 60 min. On one occasion noted in that paper it was observed that oscillations at 2 cm lead those at 3.6 cm by 4 - 5 min. Rodríguez & Mirabel (1997) have also reported a sinusoidal radio oscillation. Fender et al. (1997) discovered infrared K-band oscillations with a similar amplitude and period and interpreted these as high-frequency synchrotron counterparts to the radio oscillations, originating in repeated small ejections of plasmons from the system (the first suggestion of infrared synchrotron emission associated with the source was made by Sams, Eckart & Sunyaev (1996) from imaging observations of an infrared jet).

Quasi-periodic dips and flickering were also observed in X-rays, primarily with the XTE PCA (e.g. Greiner, Morgan & Remillard 1996; Morgan, Remillard & Greiner 1997). These have been interpreted by Belloni et al. (1997a, 1997b) as due to repeated disappearance and refilling of the inner few hundred km of the accretion disc. Radio observations simultaneous with PCA observations in 1996 October (PF97) revealed that the radio oscillations are related in phase to the major X-ray cycles, and hence with the disappearance of the inner disc according to the Belloni model. From these multiwavelength observations, the idea was formed that during repeated disappearances of the inner accretion disc, the
Figure 1. Simultaneous radio (2 cm) and infrared K-band (2.2 $\mu$m) light curves of GRS 1915+105. The infrared data have been dereddened by $A_K = 3.3$ mag. The oscillations are clearly very similar across 4 decades of energy, and seem to originate in a common population of synchrotron-emitting electrons. The emission at 2.2 $\mu$m appears to lead that at 2 cm by about 7 or 33 min, depending on which radio peak is identified with the IR peak. The estimated errors for each data point are indicated.

majority of which may be advected into the black hole, some fraction of the inner disc was accelerated and ejected from the system and observed as synchrotron-emitting plasmons (Fender et al. 1997; PF97).

Recently this general outline appears to have been confirmed by simultaneous infrared/X-ray (Eikenberry et al. 1998, hereafter E98), and infrared/X-ray/radio (Mirabel et al. 1998, hereafter M98) observations of oscillations from GRS 1915+105. In particular, E98, in high time-resolution infrared observations, have revealed a strong relation between infrared and X-ray flares, though at times the emission in the two bands can decouple. M98 report a radio and infrared oscillation in which wavelength-dependent delays appear to be compatible with a van der Laan (1966) model for synchrotron emission from an ejected plasmon, and which occurs shortly after an X-ray dip.

2 OBSERVATIONS

GRS 1915+105 was observed between 20:34 and 01:19 on 1997 September 14/15 UT with the WHIRCAM infrared camera on the William Herschel Telescope (WHT) on La Palma. Observations were made primarily through the Ks (‘short K’) filter, with an effective wavelength of 2.2 $\mu$m, as well as a small number with the H filter (1.6 $\mu$m). Standard G21-15 was used for calibration at K & H, for which we assumed magnitudes of 11.76 & 11.85 respectively. Conditions were not photometric, but accurate photometry was performed relative to star ‘A’ as in Fender et al. (1997).

Radio observations at 15 GHz were made with the Ryle Telescope (Cambridge) as part of our ongoing monitoring of the system. The observing procedure is described more fully in PF97. Inspection of flux densities at 2 and 8 GHz from the Green Bank Interferometer monitoring program confirm the presence of a variable source with an approximately flat radio spectrum from 2 – 15 GHz at the epoch of our observations.

We again deredden the infrared data by $A_K = 3.3$ mag, but caution that the H-band data, combined with J- and H-band observations some 24 hr earlier, suggest that this may be a significant overestimate of the extinction to the source (these results will be discussed elsewhere). The simultaneous K-band infrared (dereddened) and 2-cm radio observations are plotted in Fig 1. Estimated errors on each data point are similar for the radio and dereddened infrared data, at around 3 mJy r.m.s., and are indicated on the figure. The relatively long gap in the IR observations resulted from an instrumental problem while changing wavebands.
3 DISCUSSION

We have observed IR and radio emission patterns which have strikingly similar shapes and flux densities. It is also known that events of this sort are closely related to the X-ray emission (PF97, M98, E98). There are many questions raised about these phenomena, including the following:

(a) Is the IR radiation synchrotron emission?
(b) How are the shapes of the pulses in IR and radio defined?
(c) Is the near-equality of the flux density at 2.2 $\mu$m and 15 GHz a coincidence?
(d) What are the phase relationships between the emission in the various wavebands, and how do these relate to the underlying causes of the emission?
(e) Why does the X-ray emission appear to decouple from that in other wavebands?
(f) Does the IR and/or the radio emission occur in material which is being ejected from the system, and if so are the geometries and velocities similar to those of the ‘superluminal’ ejections first reported by Mirabel & Rodríguez (1994)?

We consider some of these issues briefly here.

3.1 The IR emission mechanism

The similarity between the IR and radio emission profiles and flux densities suggests that the mechanism, assumed to be synchrotron emission for the radio, is the same (Fender et al 1997). E98 argue that, because of the way in which the IR and X-ray emissions decouple, the IR cannot represent reprocessed X-ray emission. A convincing IR polarimetric observation during these quasi-periodic oscillations, and/or the detection of non-thermal brightness temperatures (perhaps via very rapid variations?) would add support to the synchrotron model.

3.2 Pulse shape and phase relationships

The pulse shape in the radio regime appears most frequently to have a short (<5 min) risetime and a somewhat slower decay, typically 10 – 20 min (PF97) with some variation between events. The IR data from E98, which have a higher time-resolution, generally appear to conform to this picture, although there are also some faster changes in the flux density.

The time-scales may be influenced by any or all of the following phenomena:

(i) the rate of supply of energy to the emission region;
(ii) light travel time across the emission region;
(iii) radiative losses of the emitting particles;
(iv) expansion of the emission region, with consequent changes in optical depth, particle energy and magnetic field strength.

M98 apply the last of these in the form of a ‘van der Laan’ (1966) expanding synchrotron emission region. In this class of model, an expanding volume of synchrotron-emitting material becomes optically thin at progressively lower frequencies while the electrons and magnetic field both lose energy. From one event (1997 May 15) for which they have infrared and three-frequency radio data M98 use the observed ratios of the peak radio flux densities to derive an index $p$. 

\[ p \]
for the distribution of the electron energies \((N(E) \propto E^{-p})\)
and delay from the initial injection of energy. The delay is
consistent with the timing of the preceding IR peak, and
the index derived is near zero, which is substantially harder
than values often found for synchrotron IR sources, and would
suggest a much greater IR flux density than that observed.
It is also difficult to reconcile the similarity of the IR and 15-
GHz pulse rise-times, which on this model are determined
by the changes in opacity, with the expectation that the syn-
chrotron region would be optically thin to IR radiation from
the time of the initial injection.

Other authors have invoked jet-like geometries to ac-
count for the spectra and variations of variable sources:
Hjellming & Johnston (1988) formulated a conical-sheath
model for the context of X-ray binaries, and others have
considered similar problems in relation to the variable, flat-
spectrum emission from the cores of AGN (e.g. Marsh &
Gear 1985, O'Dell 1988). Variants of such models may apply
here, but until we have some better idea of the geometry of
the outbursts in GRS 1915+105, application of these models
may be speculative. It appears that some expanding-source
model will be required to fit the radio-frequency data, but
it is not yet clear what combination of physics defines the
shape of the IR pulses and why it is so similar to that of the
radio.

More simultaneous observations, including all of X-ray,
IR and radio, are needed to understand how the different
emissions are related.

It is important to establish the delay, or range of delays,
between the infrared and radio peaks. M98 report a delay
\((2.2 \mu m \text{ to } 3.6 \ cm)\) of 40 min on 97 May 15; and 16 min
on 1997 Sep 09. We note, however, that there are few cycles
of data for any of the infrared measurements, and the mea-
surement of the delay is ambiguous; that on 1997 Sep 09,
when the radio oscillations had a period of 40 min, might be
56 min. Similarly, our observations on 1997 Sep 14-15 (radio
period 26 min) are compatible with a delay of 7 min (Fig
2), or possibly 33 or 59 min \((2.2 \mu m \text{ to } 2 \ cm)\). The delay of
33 min gives a marginally better subjective fit, while with a
delay of 59 min there is no longer any overlap for the sec-
cond group of IR data. We assume always that the infrared
precedes the radio emission; an attempt to fit our data with
the delay reversed, that is 15-GHz pulses preceding the IR,
is not successful unless different delays apply for the two
sections of IR data. Identification of the range of observed
delays can only be done with extended observations when
the source is in a less regular state (for example, when a
change from one period to another is seen, or isolated pulses
occur – see examples in PF97 for the radio, and the infrared
data for 1997 Aug 14-15 in E98).

It also appears from the limited data so far that some
of these delays vary between observations. Does this reflect
differing properties of the various emission regions? Or is
it perhaps a geometrical effect, where the apparent delay
changes with the relative orientation of some emitting struc-
ture and the line of sight? Determination of the true infrared
– radio delay, and its range of variation, will be crucial in
modelling the oscillations.

### 3.3 Ejection?

Observations to determine the proper motions of these tran-
sient features do not yet appear feasible. A search for spec-
tral lines in the IR would be difficult, and may show nothing
if the emission is dominated by the synchrotron process. A
naive application of “minimum energy” arguments to a syn-
chrotron source, though subject to many caveats (e.g. Leahy
1991), with a size defined by the 10-min light-travel time and
assuming one proton for every electron, yields a rest-mass of
the order of \(10^{20} \text{ g} \) – comparable with the total mass (about
\(10^{22} \text{ g}\) estimated to be removed from the disc in one 25-min
cycle in the model of Belloni et al (1997b).

### 4 CONCLUSIONS

We have presented simultaneous infrared and radio obser-
vations of GRS 1915+105 demonstrating the similarity of
oscillations, in period, shape and amplitude, over more than
4 decades of energy. The radio observations appear to lag
the infrared by 7 min plus some multiple of the oscillation
period. Coupled with the observations of Fender et al. (1997)
and M98, there seems little doubt that we are observed syn-
chrotron oscillations between (at least) 15 GHz and 2.2 \(\mu m\)
from GRS 1915+105.

However, a clear model of the emission from radio to in-
frared wavelengths, and its relation to the X-ray oscillations,
has still not been established. Expanding synchrotron source
models may reproduce the observed emission and delays, de-
pending on what we accept as the true delay between emis-
sion at infrared and radio wavelengths. Simultaneous obser-
vations at intermediate (i.e. submillimetre) wavelengths may
help to clarify the situation. Simple van der Laan models as
applied by M98 do not immediately explain the similarity
of flux densities and shapes of the pulses in the IR and radio
regimes.

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