ELECTROMAGNETIC RADIATION FROM COLLIDING BLACK HOLES

SUMMARY

It is shown that the collision of two black holes would result in the emission of electromagnetic radiation with a very distinctive wave form. If, as Hawking has suggested, the gravitational radiation events reported by Weber are produced by black hole collisions in the galactic center, then the associated electromagnetic pulses would have, in the microwave band, a maximum flux of 6×10^{-5} f.u. This flux lies at the limit of detectability with present day radio astronomy technology.

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Joseph Weber's announcement[1] of the apparent detection of gravitational wave pulses has attracted considerable attention from the scientific community. And for good reason - the characteristics of this radiation are extraordinary: the radiation seems to be produced in the galactic center,[2] but it has an average total flux[3] in the vicinity of the earth of $0.3 \times 10^{5-6}$ erg cm^{-2}sec^{-1}, a total flux comparable to the solar constant (1.4×10^{6} erg cm^{-2}sec^{-1})! Furthermore, the radiation appears to be emitted in the form of intense, short bursts at the rate of 10^{4} bursts per year with each burst having a magnitude of 10^{8-9} erg cm^{-2} in earth's vicinity.[3] Weber's observations have yet to be confirmed by other workers in gravitational wave astronomy (see papers by Tyson, Drever, and Kafka in reference 4), but this could be due to various experimental difficulties. Consequently, it behooves us to look for some other method of checking Weber'a claims.

One approach would be to look for electromagnetic pulses from the galactic center which could be associated with Weber's pulses. Indeed, several groups[5-8] have looked for such pulses, with generally negative results. Partridge *et al*,[8] for example, were unable to find a significant number of pulses of duration 0.1 to 100 sec with a flux above 27 f.u. These observations place stringent limits on the possible sources; as Hawking has pointed out,[9] the only currently viable explanation for Weber's events that is consistent with both the gravitational and electromagnetic observations is a series of black hole collisions. Hawking has given an estimate of the masses of the black holes involved in these collisions as follows: the magnitudes of the bursts reported by Weber would require the conversion into radiation of about 30 $M_{\odot}$ of rest mass energy, while a collision and merger between two black holes with zero intrinsic angular momentum could convert at most $\sim$ 30% of the rest mass of the original black holes into gravitational radiation.[10] Guessing that the process is about 50% efficient (this is probably fairly accurate; see ref. 11), we find that the colliding black holes have masses $M \simeq 100\ M_{\odot}$. In addition, we expect the bandwidth of the emitted gravitational radiation to be $1/\tau$ where $\tau = 2GM/c^3$. Setting this bandwidth equal to the operating frequency of Weber's detectors (1,661 Hz) again yields $M \sim 100 M_{\odot}$.

So a typical Weber event is envisioned to be produced in the galactic center by the collision and merger of two black holes, each having a mass $M = 100\ M_{\odot}$. The purpose of this paper is to calculate the electromagnetic spectrum associated with this collision. Now the primary emission mode of electromagnetic radiation for both the two initial black holes and the final black hole will be synchrotron radiation from matter accreted from the interstellar medium.[12] It will be shown that Flux $\propto (c/u)^4$ where c is the speed of light and u is the velocity of a black hole with respect to the interstellar medium. Since $u \sim 0$ for the final black hole, but $u \sim c$ for the two initial black holes shortly before collision, we expect that the flux will be negligible for quite some time ($\sim$ one year) before the collision, will increase suddenly (rise time between 10-100 msec) at the time of collision, and decrease very, very slowly as the final black hole is accelerated by other black holes.[10]

To see this in more detail, recall that the flux is defined to be the energy emitted per unit time per Hz per unit area. Now Shvartsman has shown [13] that even when u is much greater than the speed of sound in the ambient medium, the accretion is approximately spherically symmetric. Thus the resulting emission should also be approximately spherically symmetric. Hence, we have

$$\text{Flux} \equiv \frac{d^3E}{dA\,d\nu\,dt} \simeq \frac{dL/d\nu}{4\pi r^2} \tag{1}$$

where L is the luminosity. Since the flux will consist primarily of synchrotron radiation,[12,13] and since we will be interested in the flux at frequencies far below the critical frequency, we will follow Shvartsman[13] and write $dL/d\nu = A\,\nu^{1/3}$. (Shvartsman has shown that this estimate for the power spectrum will be valid down to the radio frequencies; in particular, it will be valid in the microwave region, which is where we will measure the flux.) The factor A can be evaluated by noting that for synchrotron radiation, a fairly good estimate of the total luminosity can be obtained by writing

$$L_{synch} \simeq \int_0^{\nu_{crit}} \frac{dL}{d\nu}\,d\nu = A\int_0^{\nu_{crit}} \nu^{1/3}\,d\nu = \frac{3}{4}A\,\nu_{crit}^{4/3} \tag{2}$$

where ν_{crit} is the critical frequency. So, solving for A and substituting into equation (1), we obtain

$$\frac{d^3E}{dA\,d\nu\,dt} \simeq \frac{L_{synch}\left(\frac{\nu}{\nu_{peak}}\right)^{1/3}}{48 r^2\,\nu_{peak}} \tag{3}$$

having used the relation $\nu_{peak} = 0.29\,\nu_{crit}$, ν_{peak} being the frequency at which the spectrum peaks. (I've been somewhat cavalier in treating the thermal synchrotron spectrum like the synchrotron spectrum emitted by a single particle, but the spectra are expected to be quite similar; see references 12 and 13.)

We wish to write the flux as a function of velocity; we do this by noting that the expressions in Novikov & Thorne[12] for L_{synch} and ν_{peak} in the case of a black hole at rest with respect to the interstellar medium are easily generalized to the moving case by making the replacement

$$\frac{T_\infty}{10^4\,{}^\circ K} \rightarrow \left[\left(\frac{u}{10\ km\ sec^{-1}}\right)^2 + \left(\frac{a_\infty}{10\ km\ sec^{-1}}\right)^2\right]$$

where a_∞ is the velocity of sound in the interstellar medium far from the black hole.

Thus, the formulae in Novikov & Thorne become

$$L_{synch} \simeq 10^{29}\,ergs\ sec^{-1}\left(\frac{M}{M_\odot}\right)^3\left(\frac{\rho_\infty}{10^{-24}\,gm\ cm^{-3}}\right)^2\left[\left(\frac{u}{10\ km\ sec^{-1}}\right)^2+\left(\frac{a_\infty}{10\ km\ sec^{-1}}\right)^2\right]^{-3}$$

$$\nu_{peak} \simeq (7\times10^{14}\,Hz)\left(\frac{\rho_\infty}{10^{-24}\,gm\ cm^{-3}}\right)^{\frac{1}{2}}\left[\left(\frac{u}{10\ km\ sec^{-1}}\right)^2+\left(\frac{a_\infty}{10\ km\ sec^{-1}}\right)^2\right]^{-\frac{3}{4}} \quad (4)$$

Substituting equations (4) into equation (3), we get

$$\frac{d^3E}{dA\,d\nu\,dt} \simeq 3\times10^{-2}\,f.u.\left(\frac{M}{M_\odot}\right)^3\left(\frac{\rho_\infty}{10^{-24}\,gm\ cm^{-3}}\right)^{4/3} d^{-2}\left(\frac{\nu}{7\times10^{14}\,Hz}\right)^{1/3} \times\left[\left(\frac{u}{10\ km\ sec^{-1}}\right)^2+\left(\frac{a_\infty}{10\ km\ sec^{-1}}\right)^2\right]^{-2} \quad (5)$$

with M being the mass of the black hole, ρ_∞ the density of the interstellar medium far from the hole, and d the distance from earth in parsecs.

During the period before collision when the two initial black holes are quite far apart, they will behave as two Newtonian point masses. Thus, for two equal mass black holes with zero velocity at infinity, we can relate the velocity u to the separation distance r :

$$r = \frac{GM}{u^2} = 1.5\ \mathrm{km}\left(\frac{M}{M_\odot}\right)\left(\frac{c}{u}\right)^2 \qquad (6)$$

The time before collision is in this case

$$t \simeq -\int_r^0 \frac{dr}{u} = 9 \times 10^7 \sec\left(\frac{M}{M_\odot}\right)\left(\frac{10\ \mathrm{km\,sec^{-1}}}{u}\right)^3 \qquad (7)$$

(The non-Newtonian period will be neglibile compared with the Newtonian, so it is a good approximation to take $r = 0$ as the lower limit in (7).) Thus for a long time before collision, the flux will be approximately zero; for $u = 100$ km/sec - two 100 $M_\odot$ black holes will have reached this velocity about a year before collision - the flux will be down by four orders of magnitude from its $u \sim 0$ value.

The two black holes will merge, emit a tremendous burst of gravitational radiation, and then settle down to a single Kerr black hole - all in a time period of about $\tau = 2GM/c^3 \sim 1$ msec for two initial 100 $M_\odot$ holes. The final black hole will have a velocity $u \sim 0$, since the gravitational radiation pulse will have zero net momentum about the initial center of mass of the two 100 $M_\odot$ black holes.(The radiation emitted before merger will definitely have this angular distribution;[15] for the case considered here - the two initial black holes have equal mass - the "coalescence radiation" should, by the symmetry about the line of centers, have the same property. What the distribution of the coalescence radiation would be if the masses are unequal is an open question.[11] Here I will assume the final velocity distribution to be the same as the initial.) The final black hole, then, will be a normal black hole whose electromagnetic flux will be given by equation (5).

Thus, were we to graph the flux of the black hole collision vs. time, we would graph a step function: zero flux for a long time ($\sim$ one year) before the moment of collision, followed by a rapid rise (the rise time would be at most the "fluctuation time" of a hole: $\Delta t \sim (10^{-3}$ to $10^{-4}\,\mathrm{sec})(M/M_0) = 10^{-1}$ to 10^{-2} sec, see ref. 12 for a detailed discussion.) to a final, relatively high constant flux. For Hawking's picture of a Weber event, we expect to have a final black hole with mass $= 170\ M_0$, $d = 10^4$ parsecs, $u = 0$, and $a_\infty = 10$ km/sec. (see ref. 12 for justification of this a_∞ value); for ρ_∞ we will take Oort's estimate[15] for the average gas density in the galactic center: $\rho_\infty = 0.5 \times 10^{-24}\,\mathrm{gm/cm^3}$. Also, in order to reduce interstellar extinction and dispersion of the pulse[8], we will want to look for the electromagnetic radiation in the GHz band, so we will set $\nu = 7 \times 10^9$ Hz. At this frequency, the expected dispersion delay is less than a second.[6]

For these values, we obtain a flux of 6×10^{-6} f.u. This number should be taken with a grain of salt, for there are several uncertainties in the calculation. First of all, Oort has pointed out[15] that the gas density of the galactic center could be larger than the value quoted above by a factor of 10^2, and it's quite possible the black hole collisions take place inside a gas cloud - gas clouds with densities as high as $10^{-18}\,\mathrm{gm/cm^3}$ have been observed.[16] Secondly, the calculation leading to (5) assumed the interstellar medium to have zero angular momentum; Pringle, Rees, and Pacholczyk have shown[17] that if the medium carries even a small amount of angular momentum, the luminosity (and hence the flux) would be increased by a factor of at least $10-10^2$. Finally, the initial velocities of the black holes with respect to the medium could be nonzero. From equation (5), we see that the flux will be comparable to the above number if $0 \leq u \leq 10$ km/sec, so out of Weber's 10^4 events per year, how many would involve black holes with final velocities in this range ? To answer this question, we will have to make an estimate of the velocity distribution of the supposed black holes in the galactic center. Let us take as a reasonable guess a gaussian distribution with $\sigma = 1000$ km/sec. (Compare this dispersion with $\sigma \sim 100$ km/sec for the stars in the center of M31.[18] Under these assumptions, we will have around 80 final black holes in the 0 - 10 km/sec velocity range. The net effect of these three factors will be to increase the flux at least an order of magnitude above the value calculated from (5).

In summary, then, we expect to find about 80 step - function - like pulses per year coming from the galactic center with a flux of 6×10^{-5} f.u. at 7×10^9 Hz. (If the holes are in a dense gas cloud, the luminosity could go as high as the Eddington limit[12] $L = (1.3 \times 10^{38}$ erg/sec$)(M/M_\odot)$. This would occur for $(\rho_\infty)/(10^{-24}$gm/cm$^3) = 360$ and would give a maximum flux of 8×10^{-3} f.u.) Could these pulses, which have fluxes about seven orders of magnitude below present experimental upper limits,[7,8] be observed? Using a gravity telescope to give the turn-on time of the pulse and a 12 hour integration time on the radio telescope (comparing the integrated flux before and after the turn-on), we could reach the limit of sensitivity of the radio telescope. For the Westerbork Synthesis Radio Telescope, with a 12 hour integration and complete synthesis, this limit is about 4×10^{-4} f.u.[19], and this limit is typical of the most sensitive radio telescopes in operation today. For the VLA telescope being built by the National Radio Astronomy Observatory, using a bandwidth of 500 MHz, a system temperature of 20°K, 12 hour integration, and complete synthesis, the detection limit at 5 GHz would be[20] 1.7×10^{-5} f.u.

Thus, if black hole collisions are responsible for the gravitational radiation pulses reported by Weber, the VLA telescope, used over long periods of time, could detect the associated pulses.

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Biographical Sketch

I was born and raised in Andalusia, a small town in southern Alabama. My interest in physics dates back to my kindergarten days (circa 1952) when I became fascinated with von Braun's visions of interplanetary flight. By the time I entered M.I.T. as an 18 year old freshman in 1965, however, this interest had metamorphosed into interest in fundamental physics, with particular attention to the role of Time in scientific theories. Graduating from M.I.T. in 1969, I became a graduate student at the University of Maryland, where I am now working toward a Ph.D. in General Relativity with Dieter Brill as thesis supervisor.

My outside interests include hiking, reading Russian literature and science fiction, and studying history and philosophy.

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