Draft version April 6, 2020
Typeset using LaTeX default style in AASTeX63

On the opacity of the event horizon to changing magnetic fields

John Reid

(Received June 1, 2019; Revised January 10, 2019; Accepted April 6, 2020)

Submitted to ApJL

ABSTRACT

Electromagnetic waves cannot escape from a black hole. Hence information about changed electromagnetic conditions inside a black hole carried by an electromagnetic wavefront cannot escape either. Electrostatic fields are unaffected by the event horizon, so it must be changes in the magnetic component of the electromagnetic wave which cannot penetrate it; the event horizon must be opaque to magnetic field changes. Gravitational waves are described by the same equations and have the same velocity as electromagnetic waves. They too cannot escape a black hole and the event horizon must also be opaque to gravitomagnetic field changes. This opacity leads to the generation of short-lived, electromagnetic and gravitoelectromagnetic shocks whenever a massive object is absorbed by a black hole. Two implications of this proposition are discussed: the excitation of plasmas in relativistic jets and the redistribution of angular momentum within galaxies.

Keywords: Gravitational waves, Black hole physics, Galaxy dynamics

1. INTRODUCTION

There are aspects of contemporary cosmology which suggest that something is missing from our understanding of the physics of black holes. Theoretically black holes should be sinks rather than sources of both matter and energy. So why is so much energy associated with observed black holes? Why does the energy of their relativistic jets appear to be leaving rather than entering them. Why are such jets so highly structured and collimated? At galactic scales dark matter is widely used to explain the flat distribution of star velocities in galaxies, but independent evidence of its existence is still to be found. The Kerr metric of a rotating black hole is an exact solution of the Einstein field equations and implies the existence of a complex ergosphere surrounding a rotating black hole, but, to date, there have been no unequivocal observations of such a phenomenon.

At a theoretical level, cosmology is largely based on the concept of the continuum whereby space-time is assumed to be continuous and differentiable almost everywhere. Experience has shown that such continuum theories are not universally applicable. They are incomplete. Maxwell's equations of electromagnetism cannot describe quantum phenomena. The Navier-Stokes equations of fluid dynamics treat every fluid as a continuum but they cannot account for the distribution of turbulent energy with wavenumber. This requires the stochastic approach of Kolmogorov (1941). Neither can these equations allow for the Gibbs entropy associated with such turbulence (Reid 2019). In fluids turbulent behaviors such as vortex shedding and wave breaking are commonly generated at phase boundary discontinuities. In space-time the event horizon of a black hole is a discontinuity analogous to a phase boundary in a fluid. Einstein's field equations are similarly incomplete and, in this case, can be augmented by the equations of electromagnetism and gravitoelectromagnetism.

A simple mechanism is proposed whereby the event horizon of a black hole is opaque to changes in both magnetic field and gravitomagnetic fields. This is not unreasonable. If a current circuit associated with "locked-in" field lines were to suddenly appear inside the event horizon then information about its appearance would take the form of an electromagnetic wave front. Such a wave front, traveling at the velocity of light, would be unable to penetrate the

Corresponding author: John Reid
johnsinclairreid@gmail.com

event horizon. The field lines locked into any plasma falling into the black hole would thereby become discontinuous at the event horizon. Such broken field lines would immediately reconnect and in so doing impart energy to external plasma. In this way some of the gravitational energy lost by the absorbed plasma goes to heating the remaining plasma by magnetic field line reconnection.

A similar thing happens to the gravitomagnetic field but with a different effect, viz. angular momentum lost to the black hole is redistributed to the accretion disk and further afield.

2. THE MAXWELL-GEM EQUATIONS

The idea of a gravitional analogue to Maxwell's electromagnetic field equations was first proposed by Heaviside (1893). These are the gravitoelectromagnetic or "GEM" field equations. Both sets of equations can be written in the same form as

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon} \tag{1}$$

$$\nabla \cdot \mathbf{B} = \mathbf{0} \tag{2}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathbf{t}} \tag{3}$$

$$\nabla \times \mathbf{B} = \frac{\mathbf{1}}{\mathbf{v^2}} \left(\frac{\mathbf{J}}{\epsilon} + \frac{\partial \mathbf{E}}{\partial \mathbf{t}} \right) \tag{4}$$

where:

- $\mathbf{E}$ is the electrostatic field or conventional gravity (i.e. $\mathbf{g}$),
- $\mathbf{B}$ is the magnetic field or the gravitomagnetic field (i.e. $\mathbf{\Omega}$),
- ρ is the charge density or the mass density,
- $\mathbf{J}$ is the electric current density or mass current density,
- ϵ is the permittivity and
- $\mathbf{v}$ is the speed of wave propagation.

and the relevant constants are shown in Table 1.

symbol	name	Maxwell	GEM
ϵ	permittivity	ϵ_0	$-\frac{1}{4\pi G}$
v	velocity	c	c_g

Table 1. Constants of the Maxwell/GEM equations. ϵ_0 is the permittivity of free space, G is Newton's gravitational constant, c is the velocity of light and c_g is the velocity of gravitational waves.

The negative sign of the gravitational permittivity reflects the fact that masses attract whereas like electric charges repel. Just as Maxwell's equations lead directly to electromagnetic waves without the need for a propagating medium or aether, so too do the GEM equations. Heaviside pondered "... then the striking conclusion is that the speed of gravity may even be the same as that of light". This was recently demonstrated by Abbott et al. (2017), i.e.

$$c_g = c \tag{5}$$

where c is the velocity of light.

Maxwell's equations of electromagnetism and the GEM equations are identical. This means that the wealth of expertise in handling these equations, which has accumulated since Maxwell's time, also applies to the GEM equations.

Firstly it leads to wave equations which apply to both phenomena: the wave equations in free space ($\nabla \rho = 0$) are readily derived from (1) to (4), viz.:

$$c^2 \nabla^2 \mathbf{E} - \frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{1}{\epsilon} \frac{\partial \mathbf{J}}{\partial t} \tag{6}$$

and

$$c^2\nabla^2\mathbf{B} - \frac{\partial^2\mathbf{B}}{\partial t^2} = -\frac{\nabla \times \mathbf{J}}{\epsilon} \tag{7}$$

where ∇^2 is the Laplacian. Thus gravitational waves are propagated in precisely the same way that electromagnetic waves are propagated and so, if electromagnetic waves are unable to escape from a black hole, neither are gravitational waves.

Secondly, gravitational waves can be plane polarized, in which case the **E** plane wave is normal to **B** plane wave and the ratio of their amplitudes is the impedance, Z, given by

$$\sqrt{\frac{\mu}{\epsilon}} = Z = \frac{E}{H} = \mu\frac{E}{B} \tag{8}$$

There is no obvious GEM analogy to the magnetic permeability, μ, which was originally devised to account for the amplifying effect of ferromagnetic materials. However this easily remedied using the relationship $c^2 = 1/\epsilon\mu$ whereby (8) becomes

$$E = cB \tag{9}$$

where E and B are the amplitudes of the gravitational and gravitomagnetic components of a plane polarized wave in free space and c is the velocity of light.

Thirdly, the gravitomagnetic field at $\mathbf{r}$ of a mass, m, moving with velocity, $\mathbf{v}$, is given by

$$\mathbf{B} = -\frac{2G}{c^2}\frac{m\mathbf{v} \times \hat{\mathbf{r}}}{r^2} \tag{10}$$

where $\hat{\mathbf{r}}$ is a unit vector in the direction of $\mathbf{r}$.

3. THE ELECTROMAGNETIC SHOCK

In the case of the electromagnetic shock, the forcing function $\partial\mathbf{J}/\partial t$ on the right hand side of (6) describes the rate at which current density is removed from the accretion disc when plasma falls beneath the opaque event horizon. It is as if a virtual current density of equal magnitude and opposite direction were created immediately outside the event horizon. It is a current pulse in a circular antenna, the far field of which is determined by the rules of Fraunhoffer diffraction and approximated by the Fourier Transform of the antenna shape. Such an antenna has two opposed, narrow lobes normal to the plane of the antenna. This could, in principle, account for the geometry of the relativistic jets emanating from black holes normal to the plane of the accretion disc.

It is, of course, only a Newtonian approximation to the true state of affairs; electromagnetic waves emanating from a source close to the event horizon will be subject to strong gravitational lensing. A more complete account of the shape of the lobes awaits a description in terms of General Relativity.

4. THE GRAVITATIONAL SHOCK

The GEM analogue of electromagnetic induction is given by (3) where **B** is, in turn, dependent on **J** in (4) which, in general, does not vary rapidly owing to the conservation of angular momentum. However this is not the case following the absorption by a super-massive black hole of a massive body such as a star.

Consider the absorption of a star by a black hole. Let us assume the center of mass of the star approaches to within the innermost stable circular orbit of the black hole. The velocity of an object falling inward "from infinity" will be relativistic and its angular momentum considerable. Tidal forces will convert the star to a spiral filament resembling a mass density ring current with no loss of angular momentum. Ultimately the filament/ring current will fall inside the event horizon. Due to (5) (6) and (7), information about the new internal configuration of $\mathbf{J}$, $\mathbf{J}_i$, in the form of a gravitational wave front cannot pass through the event horizon. The newly-generated gravitomagnetic field is trapped inside the event horizon. To an observer outside the event horizon angular momentum has effectively disappeared from the Universe.

The gravitomagnetic field so generated will be identical with that which would be generated by the sudden appearance of a virtual ring current $\mathbf{J}_v$ at the event horizon with the opposite direction to the ring current swallowed by the black hole. By (4), during the time interval in which $\mathbf{J}_v$ is changing $\mathbf{B}$ will change and, in (3), $\partial\mathbf{B}/\partial t$ and $\nabla \times \mathbf{E}$ become non-zero, i.e. **E** becomes non-conservative for the duration of the interval and "GEM induction" will alter the angular momentum of material outside the event horizon. The change in angular momentum so induced will have the opposite direction to the virtual ring current (Shapiro 1996) and hence have the same direction as the angular momentum lost to the black hole. A GEM shock will propagate outwards as a gravitational wave front with $\mathbf{J}_v$ substituted for $\mathbf{J}$ in (6) and(7). The **B** component will be polarized in the plane defined by the direction normal to the plane defined by $\mathbf{J}_v$ and the direction of propagation, i.e. parallel to the angular momentum vector. As with electromagnetic waves, there will be an **E** component normal to the **B** component and acting so as to alter the angular momentum of the material outside the event horizon.

Now consider the interaction of this wave front with a single massive object in a rectangular coordinate system with unit vectors, $\hat{\mathbf{i}}$, $\hat{\mathbf{j}}$, $\hat{\mathbf{k}}$, centered at the object in which the galactic center is located at $R\hat{\mathbf{i}}$. Consider a gravity wave shock with gravitomagnetic component $\mathbf{B_H}$, generated at the event horizon at time, R/c, by the above-described mechanism and lasting for time, δt. The gravitomagnetic component of the shock at the object, $\mathbf{B}_s$, is given by

$$B_s\hat{\mathbf{k}} = \mathbf{B}_s = \frac{R_H^2\mathbf{B_H}}{R^2} \tag{11}$$

where R_H is the Schwartzchild radius. By (9) the gravitational component, $\mathbf{E}_s$, is given by

$$\mathbf{E}_s = cB_s\hat{\mathbf{j}} \tag{12}$$

and the velocity of the object increases tangentially by δv where

$$\delta\mathbf{v} = \int_{\delta t}\mathbf{E}_s\delta t \tag{13}$$

In this way angular momentum, seemingly lost to the black hole, is communicated to outlying parts of the galaxy.

However the physics of the gravitational wave front is more complex than this. It resembles the propagation of an electromagnetic wave in a collisionless, fully ionized plasma. Just as the induced motion of each electron in a plasma modifies the propagating wave, each massive body accelerated by the above mechanism generates its own GEM disturbance, $\delta\mathbf{B}$, as described by substituting $\delta\mathbf{v}$ for $\mathbf{v}$ in (10). These multiple disturbances will also propagate as gravitational waves superimposed on the original wave.

5. CONCLUSION

The above description provides the groundwork for a new approach to cosmology. General Relativity will be needed to describe near-field effects of the proposed event horizon opacity. Insights might be gained numerically by Lagrangian tracking of discrete particles in a simulated star field. Such modeling may well lead to unexpected outcomes regarding galactic morphology and evolution. For example, at galactic scales dark matter (Zwicky 1933) is widely used to explain the flat distribution of star velocities in galaxies as first observed by Rubin & Ford (1970), but independent evidence of its existence is lacking. The redistribution of angular momentum by successive gravitomagnetic shocks generated during the absorption of massive objects by a supermassive black hole at the galactic center may well be sufficient to account for the observed distribution. Clearly a more rigorous examination is needed but it is beyond the scope of this paper.

ACKNOWLEDGMENTS

These ideas were inspired by Geoffrey Hudson's article "A Challenge to Dark Matter".

REFERENCES

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, The Astrophysical Journal, 848, L13, doi: 10.3847/2041-8213/aa920c

Heaviside, O. 1893, The Electrician, 31, 281. http://sergf.ru/Heavisid.htm

Kolmogorov, A. N. 1941, in Dokl. Akad. Nauk SSSR, Vol. 30, 301–305

Reid, J. 2019, The Fluid Catastrophe. (Newcastle Upon Tyne, UK: Cambridge Scholars Publishing)

Rubin, V. C., & Ford, W. Kent, J. 1970, Astrophysical Journal, 159, 379, doi: 10.1086/150317

Shapiro, S. L. 1996, Phys. Rev. Lett., 77, 4487, doi: 10.1103/PhysRevLett.77.4487

Zwicky, F. 1933, Helv. Phys. Acta, 6, 110, doi: 10.1007/s10714-008-0707-4