A subject of renewed appeal

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Motivation

- The recent announcement of the detection of a gravitational wave event, and the debate that followed on whether or not it was, or should have been, accompanied by an electromagnetic signal, is likely to bring renewed interest to the field of the interaction of an electromagnetic plasma with a time varying gravitational field
- Such an interaction can take place
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  B) in the field of a gravitational wave.

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- For Case (B) there is a string of papers dating back at least from the `70s. These papers are mainly aimed at studying the conversion of gravitational waves into electromagnetic or longitudinal plasma waves from the point of view of the gravitational waves damping and/or detection, or even possibly of their generation under laboratory conditions.
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- There is an enormous imbalance in strength between electromagnetic and gravitational interactions at the particle level. *Nevertheless, it would appear natural to think that, if the huge objects that are supposed to be involved in the collapse that generated the gravitational waves are in contact with, or through their ultrastrong fields can interact with, an electromagnetic medium a fraction of the energy released must take the form of electromagnetic energy.*
- A possible conversion mechanism can be identified by observing that, while the gravitational fields per se tend to make all matter move (free fall) along the geodesics of the deformed space geometry independently of matter being charged or not, they can induce charge and current separation in the presence of electromagnetic fields.

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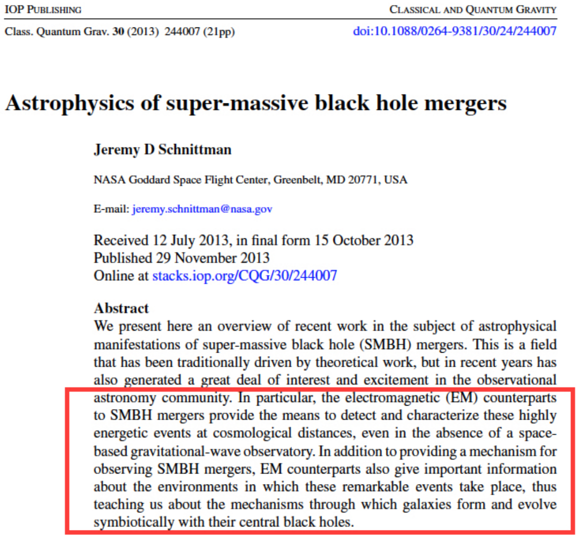

IOP PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **30** (2013) 244007 (21pp) doi:10.1088/0264-9381/30/24/244007

Astrophysics of super-massive black hole mergers

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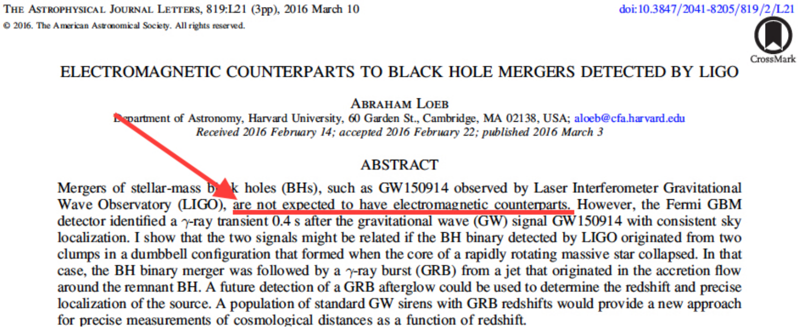
Abstract

We present here an overview of recent work in the subject of astrophysical manifestations of super-massive black hole (SMBH) mergers. This is a field that has been traditionally driven by theoretical work, but in recent years has also generated a great deal of interest and excitement in the observational astronomy community. In particular, the electromagnetic (EM) counterparts to SMBH mergers provide the means to detect and characterize these highly energetic events at cosmological distances, even in the absence of a space-based gravitational-wave observatory. In addition to providing a mechanism for observing SMBH mergers, EM counterparts also give important information about the environments in which these remarkable events take place, thus teaching us about the mechanisms through which galaxies form and evolve symbiotically with their central black holes.

Motivation



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doi:10.3847/2041-8205/819/2/L21

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ELECTROMAGNETIC COUNTERPARTS TO BLACK HOLE MERGERS DETECTED BY LIGO

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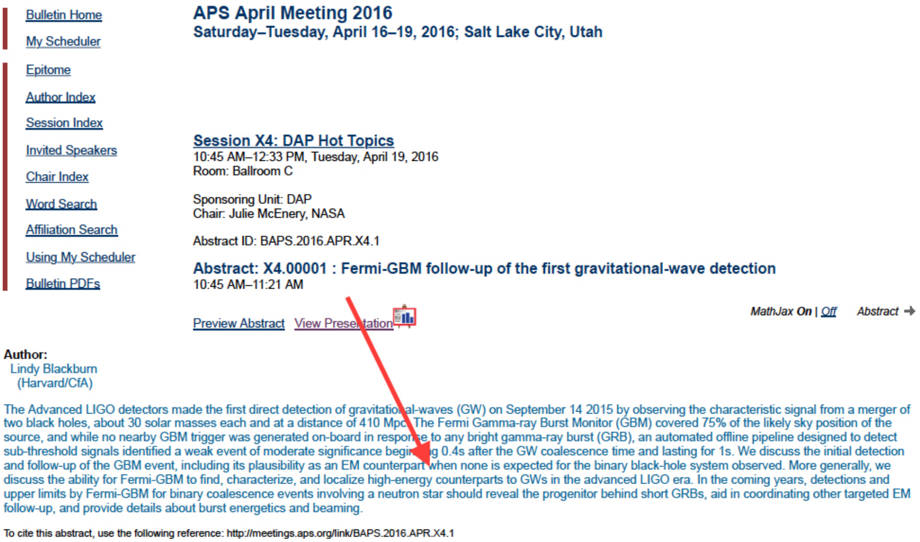
ABSTRACT

Mergers of stellar-mass black holes (BHs), such as GW150914 observed by Laser Interferometer Gravitational Wave Observatory (LIGO), are not expected to have electromagnetic counterparts. However, the Fermi GBM detector identified a γ-ray transient 0.4 s after the gravitational wave (GW) signal GW150914 with consistent sky localization. I show that the two signals might be related if the BH binary detected by LIGO originated from two clumps in a dumbbell configuration that formed when the core of a rapidly rotating massive star collapsed. In that case, the BH binary merger was followed by a γ-ray burst (GRB) from a jet that originated in the accretion flow around the remnant BH. A future detection of a GRB afterglow could be used to determine the redshift and precise localization of the source. A population of standard GW sirens with GRB redshifts would provide a new approach for precise measurements of cosmological distances as a function of redshift.

I call it “sweeper” theory.

Motivation



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APS April Meeting 2016
Saturday–Tuesday, April 16–19, 2016; Salt Lake City, Utah

Session X4: DAP Hot Topics
10:45 AM–12:33 PM, Tuesday, April 19, 2016
Room: Ballroom C

Sponsoring Unit: DAP
Chair: Julie McEnery, NASA

Abstract ID: BAPS.2016.APR.X4.1

Abstract: X4.00001 : Fermi-GBM follow-up of the first gravitational-wave detection
10:45 AM–11:21 AM

Preview Abstract View Presentation

*MathJax **On** | Off* *Abstract* ➜

Author:
Lindy Blackburn
(Harvard/CfA)

The Advanced LIGO detectors made the first direct detection of gravitational-waves (GW) on September 14 2015 by observing the characteristic signal from a merger of two black holes, about 30 solar masses each and at a distance of 410 Mpc. The Fermi Gamma-ray Burst Monitor (GBM) covered 75% of the likely sky position of the source, and while no nearby GBM trigger was generated on-board in response to any bright gamma-ray burst (GRB), an automated offline pipeline designed to detect sub-threshold signals identified a weak event of moderate significance beginning 0.4s after the GW coalescence time and lasting for 1s. We discuss the initial detection and follow-up of the GBM event, including its plausibility as an EM counterpart when none is expected for the binary black-hole system observed. More generally, we discuss the ability for Fermi-GBM to find, characterize, and localize high-energy counterparts to GWs in the advanced LIGO era. In the coming years, detections and upper limits by Fermi-GBM for binary coalescence events involving a neutron star should reveal the progenitor behind short GRBs, aid in coordinating other targeted EM follow-up, and provide details about burst energetics and beaming.

To cite this abstract, use the following reference: http://meetings.aps.org/link/BAPS.2016.APR.X4.1

Einstein's equations

Field equations

$$R_{\mu\nu} - (1/2)R\,g_{\mu\nu} + \Lambda g_{\mu\nu} = (8\pi G/c^4)\,T_{\mu\nu}$$

where $R_{\mu\nu}$ is the Ricci curvature tensor, R is the scalar curvature, $g_{\mu\nu}$ is the metric tensor, Λ is the cosmological constant, G is Newton's gravitational constant, c is the speed of light and $T^{\mu\nu}$ is the (conserved) stress-energy tensor ($T^{\mu\nu}{}_{;\nu} = 0$) of matter *and of the e.m. fields*. Note the Bianchi identity $R^{\mu\nu}{}_{;\nu} - (1/2)\,R_{;\nu}\,g^{\mu\nu} = 0$.

$$R_{\mu\nu} = R^{\alpha}{}_{\mu\alpha\nu} = \partial_\rho \Gamma^{\rho}{}_{\nu\mu} - \partial_\nu \Gamma^{\rho}{}_{\rho\mu} + \Gamma^{\rho}{}_{\rho\lambda}\Gamma^{\lambda}{}_{\nu\mu} - \Gamma^{\rho}{}_{\nu\lambda}\Gamma^{\lambda}{}_{\rho\mu}$$

$$\Gamma^{\rho}{}_{\mu\nu} = (1/2)\,g^{\rho\lambda}\,[g_{\lambda\mu,\nu} + g_{\lambda\nu,\mu} - g_{\mu\nu,\lambda}]$$

The covariant derivative is defined such that $g^{\mu\nu}{}_{;\nu} = 0$ (for a 4-vector as

$$\tau^{\mu}{}_{;\lambda} = \tau^{\mu}{}_{,\lambda} + \Gamma^{\mu}{}_{\lambda\rho}\tau^{\rho}, \ldots., \qquad \text{with} \qquad {}_{,\mu} = \partial_\mu \qquad \text{etc.)}$$

Einstein's equations: GW linearized limit

Linearize the space time metric (with proper boundary conditions at infinity) with respect to the Minkowski metric $\eta_{\mu\nu}$

$$h_{\mu\nu} = \eta_{\mu\nu} - g_{\mu\nu}$$

and use the gauge freedom[1]
Choose the TT gauge (Transverse traceless gauge)

$$\Box h^{TT}_{\mu\nu} = -(16\pi G/c^4)\, T_{\mu\nu}$$

that can be solved in a given frame in terms of the retarded potentials $h_\oplus, h_\otimes$ and involve (in the appropriate limit) the second time detivative of the quadrupole moment of the source.

$$h_{ij} = \frac{2G}{Rc^4} \ddot{Q}^{TT}_{ij}|_{ret}$$

---

[1] care with matter boundary conditions TT requires free falling matter.

Maxwell's equations in a curved space time

$$F_{\mu\nu} = A_{\nu,\mu} - A_{\mu,\nu}, \qquad F_{[\mu\nu;\lambda]} = F_{[\mu\nu,\lambda]} = 0 \qquad \text{Bianchi identity}$$

$$F^{\mu\nu}{}_{;\nu} = (-g)^{-1/2}\,[(-g)^{1/2}\,F^{\mu\nu}]_{,\nu} = (4\pi/c)\,j^{\mu}$$

$$j^{\mu}{}_{;\mu} = (-g)^{-1/2}\,[(-g)^{1/2}\,j^{\mu}]_{,\mu} = 0$$

$j^0\,(-g)^{1/2}/c = \text{charge density}$. In vacuum $[(-g)^{1/2}\,F^{\mu\nu}]_{,\nu} = 0$.

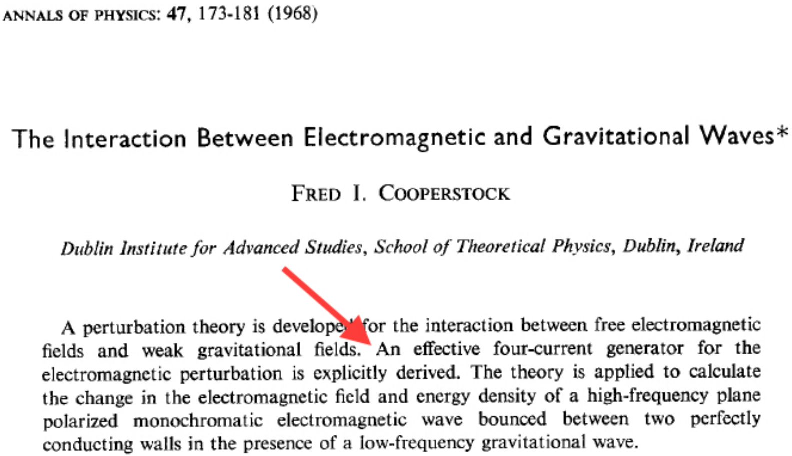
Wave equation in vacuum (with the Lorenz gauge $A^{\mu}{}_{;\mu} = 0$)

$$\Box A^{\mu} = R_{\mu\nu}\,A^{\nu} \qquad \text{covariant derivatives do not commute, } (\lambda/R)^2 \text{ effect.}$$

It can be viewed in terms of an *inhomogeneous "dielectric/magnetic" medium.* Linearized Ricci tensor (in general)

$$R_{\mu\nu} = (h^{\alpha}{}_{\mu,\nu\alpha} + h^{\alpha}{}_{\nu,\mu\alpha} - h_{\mu\nu,\alpha}{}^{,\alpha} - h_{,\mu\nu})$$

EMw - Gw interaction



ANNALS OF PHYSICS: **47**, 173-181 (1968)

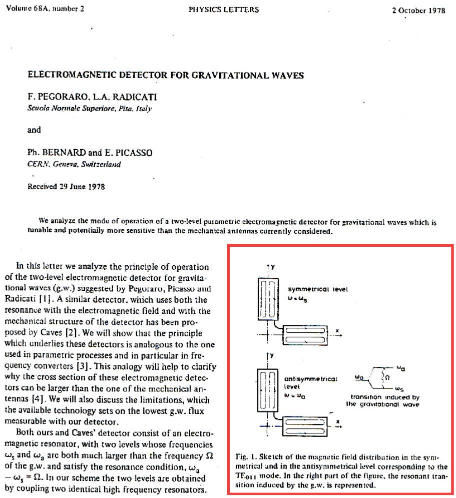
The Interaction Between Electromagnetic and Gravitational Waves*

FRED I. COOPERSTOCK

Dublin Institute for Advanced Studies, School of Theoretical Physics, Dublin, Ireland

A perturbation theory is developed for the interaction between free electromagnetic fields and weak gravitational fields. An effective four-current generator for the electromagnetic perturbation is explicitly derived. The theory is applied to calculate the change in the electromagnetic field and energy density of a high-frequency plane polarized monochromatic electromagnetic wave bounced between two perfectly conducting walls in the presence of a low-frequency gravitational wave.

E.M. gravitational wave detectors.



Volume 68A, number 2 PHYSICS LETTERS 2 October 1978

ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES

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and

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Received 29 June 1978

We analyze the mode of operation of a two-level parametric electromagnetic detector for gravitational waves which is tunable and potentially more sensitive than the mechanical antennas currently considered.

In this letter we analyze the principle of operation of the two-level electromagnetic detector for gravitational waves (g.w.) suggested by Pegoraro, Picasso and Radicati [1]. A similar detector, which uses both the resonance with the electromagnetic field and with the mechanical structure of the detector has been proposed by Caves [2]. We will show that the principle which underlies these detectors is analogous to the one used in parametric processes and in particular in frequency converters [3]. This analogy will help to clarify why the cross section of these electromagnetic detectors can be larger than the one of the mechanical antennas [4]. We will also discuss the limitations, which the available technology sets on the lowest g.w. flux measurable with our detector.

Both ours and Caves' detector consist of an electromagnetic resonator, with two levels whose frequencies ω_s and ω_a are both much larger than the frequency Ω of the g.w. and satisfy the resonance condition, $\omega_a - \omega_s = \Omega$. In our scheme the two levels are obtained by coupling two identical high frequency resonators.

Fig. 1. Sketch of the magnetic field distribution in the symmetrical and in the antisymmetrical level corresponding to the TE_{011} mode. In the right part of the figure, the resonant transition induced by the g.w. is represented.

Care with boundary conditions and gauges.

Lorentz force in a curved space time

Lorentz force on a charged massive particle

$$\partial p^{\mu}/d\tau = -\Gamma^{\mu}{}_{\alpha\beta}\, p^{\alpha} u^{\beta} + qF^{\mu}{}_{\gamma} u^{\gamma}$$

First term on the rhs describes geodesic motion, second term discriminates q/m. First term is metric, second is not.[2]
A more intrisic way of writing the force equation is

$$u^{\gamma} u^{\mu}_{;\gamma} \equiv Du^{\mu}/d\tau = (q/m)F^{\mu}{}_{\gamma} u^{\gamma}$$

In the absence of the e.m. fields the quantity of relevance is the geodesic separation ξ^{μ} which obeys the equation

$$D^2\xi^{\mu}/d\tau^2 = -R^{\mu}{}_{\alpha\nu\beta} u^{\alpha} u^{\beta} \xi^{\nu}.$$

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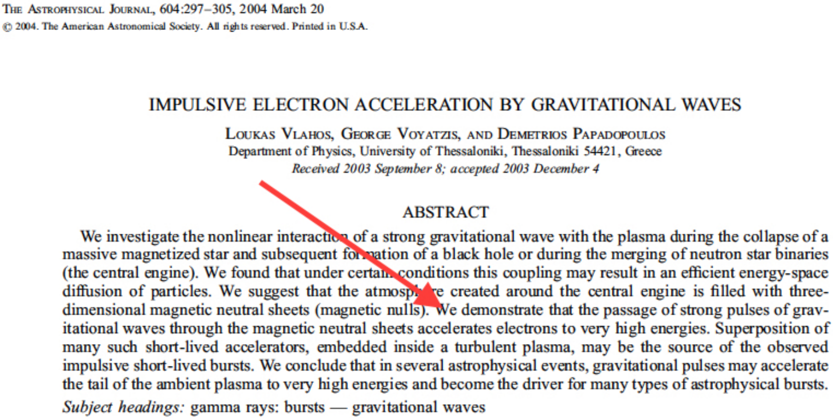
[2] Despite some attempts, e.g. by Weyl

Particle acceleration



The Astrophysical Journal, 604:297–305, 2004 March 20

IMPULSIVE ELECTRON ACCELERATION BY GRAVITATIONAL WAVES

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Department of Physics, University of Thessaloniki, Thessaloniki 54421, Greece

Received 2003 September 8; accepted 2003 December 4

ABSTRACT

We investigate the nonlinear interaction of a strong gravitational wave with the plasma during the collapse of a massive magnetized star and subsequent formation of a black hole or during the merging of neutron star binaries (the central engine). We found that under certain conditions this coupling may result in an efficient energy-space diffusion of particles. We suggest that the atmosphere created around the central engine is filled with three-dimensional magnetic neutral sheets (magnetic nulls). We demonstrate that the passage of strong pulses of gravitational waves through the magnetic neutral sheets accelerates electrons to very high energies. Superposition of many such short-lived accelerators, embedded inside a turbulent plasma, may be the source of the observed impulsive short-lived bursts. We conclude that in several astrophysical events, gravitational pulses may accelerate the tail of the ambient plasma to very high energies and become the driver for many types of astrophysical bursts.

Subject headings: gamma rays: bursts — gravitational waves

Fluid equations in curved space-time

Relativistic fluid (a closure, such as an equation for the entropy density, must be added)

$(\rho u^{\mu})_{;\mu} = 0, \quad u_{\mu} u^{\mu}{}_{;\nu} = 0,$ ρ rest frame mass energy density

$T^{\mu\nu} = (e+p)u^{\mu}u^{\nu} + pg^{\mu\nu} \quad T^{\mu\nu}{}_{;\nu} = 0,$ e rest frame total energy density

p rest frame pressure, $e = \rho(1+\varepsilon)$, ε internal energy per unit mass.

In the presence of e.m. fields, single fluid equations:
add the homogeneous Maxwell's equations

$$\mathscr{F}^{\mu\nu}{}_{;\nu} = 0, \qquad \mathscr{F}^{\mu\nu} = (-g)^{-1/2}\varepsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}/2$$

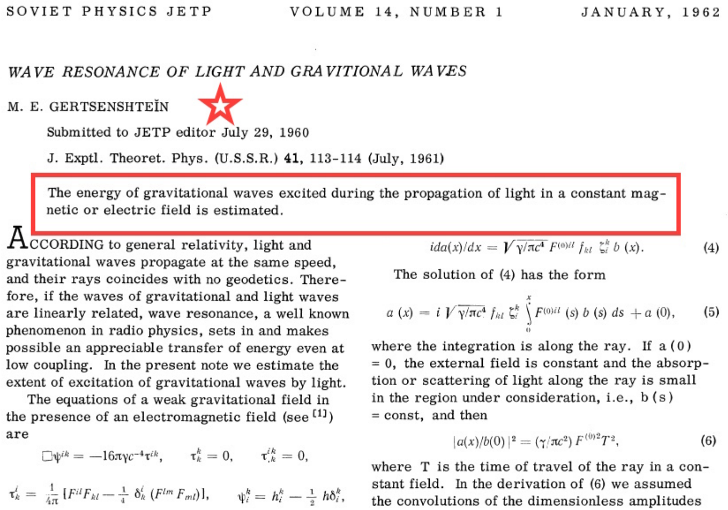
and the e.m. momentum energy tensor

$$T^{\mu\nu}_{\rm em} = [F^{\mu\alpha}F_{\alpha}{}^{\nu} - (g^{\mu\nu}/4)F_{\alpha\beta}F^{\alpha\beta}]/(4\pi)$$

In Einstein's equation it can lead to em to gw conversion

Source term quadratic in the e.m. fields : g.w. spin 2, e.m.w. spin 1.

EMW ↔ GW in the presence of a static magnetic field



SOVIET PHYSICS JETP VOLUME 14, NUMBER 1 JANUARY, 1962

WAVE RESONANCE OF LIGHT AND GRAVITATIONAL WAVES

M. E. GERTSENSHTEĬN

Submitted to JETP editor July 29, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 113-114 (July, 1961)

The energy of gravitational waves excited during the propagation of light in a constant magnetic or electric field is estimated.

ACCORDING to general relativity, light and gravitational waves propagate at the same speed, and their rays coincides with no geodetics. Therefore, if the waves of gravitational and light waves are linearly related, wave resonance, a well known phenomenon in radio physics, sets in and makes possible an appreciable transfer of energy even at low coupling. In the present note we estimate the extent of excitation of gravitational waves by light.

The equations of a weak gravitational field in the presence of an electromagnetic field (see [1]) are

$$\Box\psi^{ik} = -16\pi\gamma c^{-4}\tau^{ik}, \qquad \tau_k^k = 0, \qquad \tau^{ik}_{,k} = 0,$$

$$\tau_k^i = \frac{1}{4\pi}\left[F^{il}F_{kl} - \frac{1}{4}\delta_k^i\left(F^{lm}F_{ml}\right)\right], \qquad \psi_i^k = h_i^k - \frac{1}{2}h\delta_i^k,$$

$$i\,da(x)/dx = \sqrt{\gamma/\pi c^4}\,F^{(0)il}f_{kl}\,\zeta_i^k\,b(x). \tag{4}$$

The solution of (4) has the form

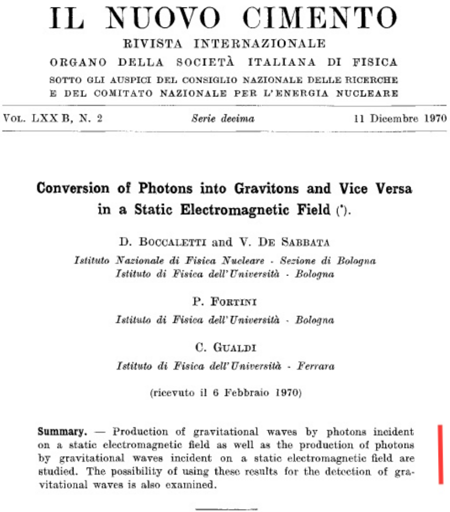
$$a(x) = i\sqrt{\gamma/\pi c^4}\,f_{kl}\,\zeta_i^k\int_0^x F^{(0)il}(s)\,b(s)\,ds + a(0), \tag{5}$$

where the integration is along the ray. If a(0) = 0, the external field is constant and the absorption or scattering of light along the ray is small in the region under consideration, i.e., b(s) = const, and then

$$|a(x)/b(0)|^2 = (\gamma/\pi c^2)\,F^{(0)2}T^2, \tag{6}$$

where T is the time of travel of the ray in a constant field. In the derivation of (6) we assumed the convolutions of the dimensionless amplitudes

EMW ↔ GW



IL NUOVO CIMENTO
RIVISTA INTERNAZIONALE
ORGANO DELLA SOCIETÀ ITALIANA DI FISICA
SOTTO GLI AUSPICI DEL CONSIGLIO NAZIONALE DELLE RICERCHE
E DEL COMITATO NAZIONALE PER L'ENERGIA NUCLEARE

VOL. LXX B, N. 2 — *Serie decima* — 11 Dicembre 1970

Conversion of Photons into Gravitons and Vice Versa in a Static Electromagnetic Field (*).

D. BOCCALETTI and V. DE SABBATA
Istituto Nazionale di Fisica Nucleare - Sezione di Bologna
Istituto di Fisica dell'Università - Bologna

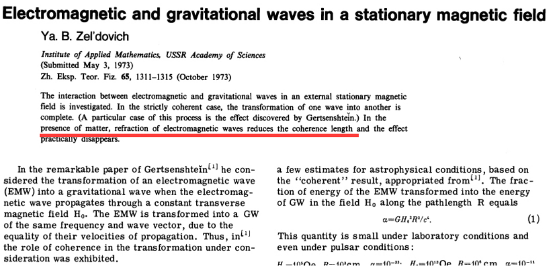
P. FORTINI
Istituto di Fisica dell'Università - Bologna

C. GUALDI
Istituto di Fisica dell'Università - Ferrara

(ricevuto il 6 Febbraio 1970)

Summary. — Production of gravitational waves by photons incident on a static electromagnetic field as well as the production of photons by gravitational waves incident on a static electromagnetic field are studied. The possibility of using these results for the detection of gravitational waves is also examined.

EMW $\leftrightarrow$ GW - Coherence problems



Electromagnetic and gravitational waves in a stationary magnetic field

Ya. B. Zel'dovich

Institute of Applied Mathematics, USSR Academy of Sciences

(Submitted May 3, 1973)
Zh. Eksp. Teor. Fiz. **65**, 1311–1315 (October 1973)

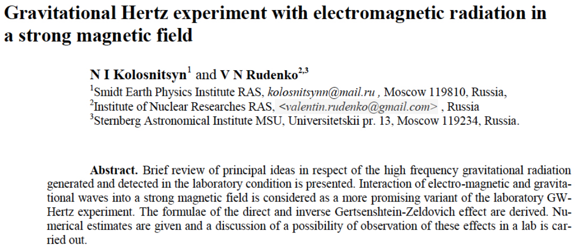
The interaction between electromagnetic and gravitational waves in an external stationary magnetic field is investigated. In the strictly coherent case, the transformation of one wave into another is complete. (A particular case of this process is the effect discovered by Gertsenshteĭn.) In the presence of matter, refraction of electromagnetic waves reduces the coherence length and the effect practically disappears.

In the remarkable paper of Gertsenshteĭn[1] he considered the transformation of an electromagnetic wave (EMW) into a gravitational wave when the electromagnetic wave propagates through a constant transverse magnetic field H_0. The EMW is transformed into a GW of the same frequency and wave vector, due to the equality of their velocities of propagation. Thus, in[1] the role of coherence in the transformation under consideration was exhibited.

a few estimates for astrophysical conditions, based on the "coherent" result, appropriated from[1]. The fraction of energy of the EMW transformed into the energy of GW in the field H_0 along the pathlength R equals

$$\alpha = G H_0^2 R^2 / c^4. \qquad (1)$$

This quantity is small under laboratory conditions and even under pulsar conditions:

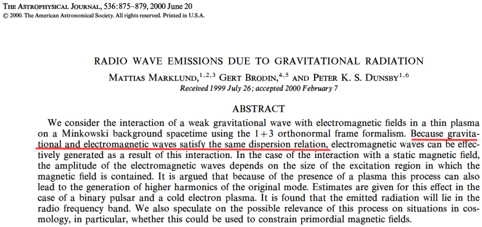


Gravitational Hertz experiment with electromagnetic radiation in a strong magnetic field

N I Kolosnitsyn[1] and **V N Rudenko**[2,3]
[1]Smidt Earth Physics Institute RAS, *kolosnitsynn@mail.ru* , Moscow 119810, Russia,
[2]Institute of Nuclear Researches RAS, <*valentin.rudenko@gmail.com*> , Russia
[3]Sternberg Astronomical Institute MSU, Universitetskii pr. 13, Moscow 119234, Russia.

Abstract. Brief review of principal ideas in respect of the high frequency gravitational radiation generated and detected in the laboratory condition is presented. Interaction of electro-magnetic and gravitational waves into a strong magnetic field is considered as a more promising variant of the laboratory GW-Hertz experiment. The formulae of the direct and inverse Gertsenshtein-Zeldovich effect are derived. Numerical estimates are given and a discussion of a possibility of observation of these effects in a lab is carried out.

GW $+$ B$_\perp$ $\rightarrow$ EMW dielectric/magnetic medium



THE ASTROPHYSICAL JOURNAL, 536:875–879, 2000 June 20

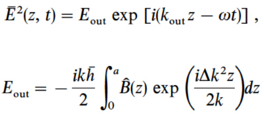
RADIO WAVE EMISSIONS DUE TO GRAVITATIONAL RADIATION

MATTIAS MARKLUND,[1,2,3] GERT BRODIN,[4,5] AND PETER K. S. DUNSBY[1,6]

Received 1999 July 26; accepted 2000 February 7

ABSTRACT

We consider the interaction of a weak gravitational wave with electromagnetic fields in a thin plasma on a Minkowski background spacetime using the 1+3 orthonormal frame formalism. Because gravitational and electromagnetic waves satisfy the same dispersion relation, electromagnetic waves can be effectively generated as a result of this interaction. In the case of the interaction with a static magnetic field, the amplitude of the electromagnetic waves depends on the size of the excitation region in which the magnetic field is contained. It is argued that because of the presence of a plasma this process can also lead to the generation of higher harmonics of the original mode. Estimates are given for this effect in the case of a binary pulsar and a cold electron plasma. It is found that the emitted radiation will lie in the radio frequency band. We also speculate on the possible relevance of this process on situations in cosmology, in particular, whether this could be used to constrain primordial magnetic fields.



$$\bar{E}^2(z,t) = E_{\text{out}} \exp\left[i(k_{\text{out}} z - \omega t)\right] ,$$

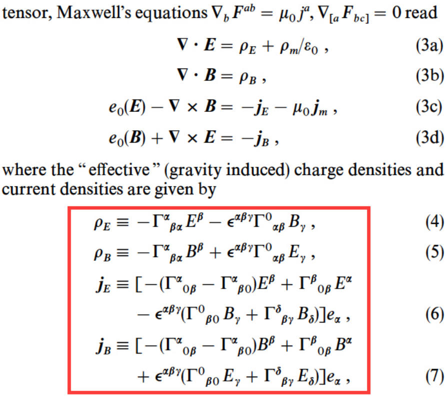
$$E_{\text{out}} = -\frac{ik\bar{h}}{2}\int_0^a \hat{B}(z) \exp\left(\frac{i\Delta k^2 z}{2k}\right) dz$$

Estimate for collapse double pulsar in interaction region $\sim 60R_s$

$h \sim 10^{-3}, \quad B \sim 10^8 T$

$E \sim 50MV/m$

$\omega/(2\pi) \leq 10^3 Hz$



tensor, Maxwell's equations $\nabla_b F^{ab} = \mu_0 j^a$, $\nabla_{[a} F_{bc]} = 0$ read

$$\nabla \cdot \boldsymbol{E} = \rho_E + \rho_m/\varepsilon_0 , \tag{3a}$$

$$\nabla \cdot \boldsymbol{B} = \rho_B , \tag{3b}$$

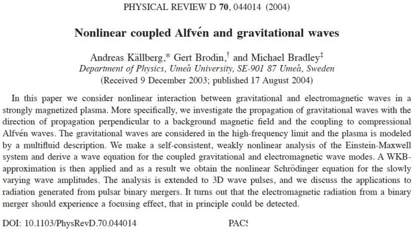
$$e_0(\boldsymbol{E}) - \nabla \times \boldsymbol{B} = -\boldsymbol{j}_E - \mu_0 \boldsymbol{j}_m , \tag{3c}$$

$$e_0(\boldsymbol{B}) + \nabla \times \boldsymbol{E} = -\boldsymbol{j}_B , \tag{3d}$$

where the "effective" (gravity induced) charge densities and current densities are given by

$$\boxed{\begin{aligned}
\rho_E &\equiv -\Gamma^\alpha{}_{\beta\alpha} E^\beta - \epsilon^{\alpha\beta\gamma}\Gamma^0{}_{\alpha\beta} B_\gamma , && (4)\\
\rho_B &\equiv -\Gamma^\alpha{}_{\beta\alpha} B^\beta + \epsilon^{\alpha\beta\gamma}\Gamma^0{}_{\alpha\beta} E_\gamma , && (5)\\
j_E &\equiv [-(\Gamma^\alpha{}_{0\beta} - \Gamma^\alpha{}_{\beta 0})E^\beta + \Gamma^\beta{}_{0\beta} E^\alpha \\
&\quad - \epsilon^{\alpha\beta\gamma}(\Gamma^0{}_{\beta 0} B_\gamma + \Gamma^\delta{}_{\beta\gamma} B_\delta)] e_\alpha , && (6)\\
j_B &\equiv [-(\Gamma^\alpha{}_{0\beta} - \Gamma^\alpha{}_{\beta 0})B^\beta + \Gamma^\beta{}_{0\beta} B^\alpha \\
&\quad + \epsilon^{\alpha\beta\gamma}(\Gamma^0{}_{\beta 0} E_\gamma + \Gamma^\delta{}_{\beta\gamma} E_\delta)] e_\alpha , && (7)
\end{aligned}}$$

$\mathrm{GW} + B_\perp \to \mathrm{EMW}$ dielectric/magnetic medium



PHYSICAL REVIEW D **70**, 044014 (2004)

Nonlinear coupled Alfvén and gravitational waves

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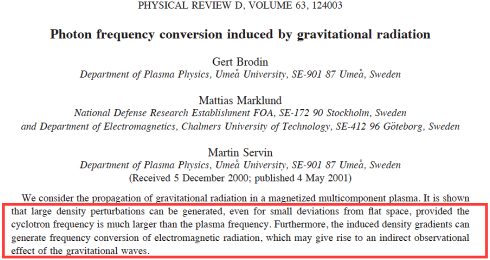
(Received 9 December 2003; published 17 August 2004)

In this paper we consider nonlinear interaction between gravitational and electromagnetic waves in a strongly magnetized plasma. More specifically, we investigate the propagation of gravitational waves with the direction of propagation perpendicular to a background magnetic field and the coupling to compressional Alfvén waves. The gravitational waves are considered in the high-frequency limit and the plasma is modeled by a multifluid description. We make a self-consistent, weakly nonlinear analysis of the Einstein-Maxwell system and derive a wave equation for the coupled gravitational and electromagnetic wave modes. A WKB-approximation is then applied and as a result we obtain the nonlinear Schrödinger equation for the slowly varying wave amplitudes. The analysis is extended to 3D wave pulses, and we discuss the applications to radiation generated from pulsar binary mergers. It turns out that the electromagnetic radiation from a binary merger should experience a focusing effect, that in principle could be detected.

DOI: 10.1103/PhysRevD.70.044014 PAC



PHYSICAL REVIEW D, VOLUME 63, 124003

Photon frequency conversion induced by gravitational radiation

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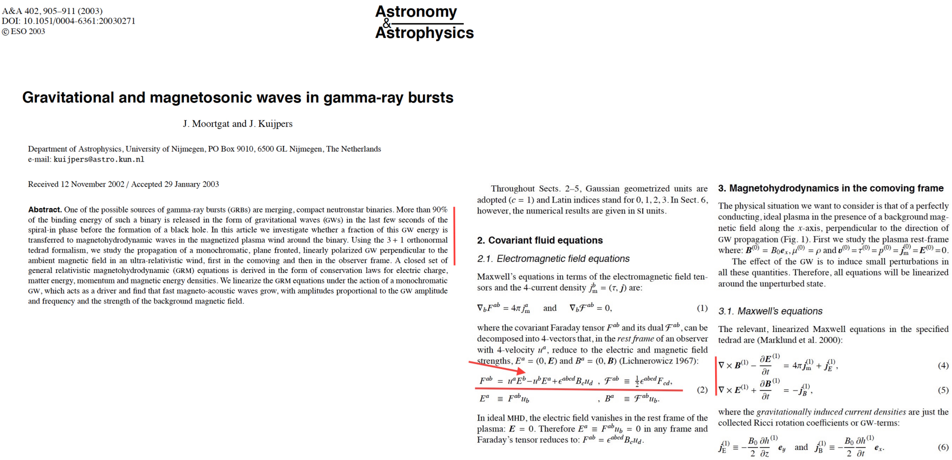
(Received 5 December 2000; published 4 May 2001)

We consider the propagation of gravitational radiation in a magnetized multicomponent plasma. It is shown that large density perturbations can be generated, even for small deviations from flat space, provided the cyclotron frequency is much larger than the plasma frequency. Furthermore, the induced density gradients can generate frequency conversion of electromagnetic radiation, which may give rise to an indirect observational effect of the gravitational waves.

GW + $B_\perp \rightarrow$ EMW dielectric/magnetic medium



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DOI: 10.1051/0004-6361:20030271
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Astronomy & Astrophysics

Gravitational and magnetosonic waves in gamma-ray bursts

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Abstract. One of the possible sources of gamma-ray bursts (GRBs) are merging, compact neutronstar binaries. More than 90% of the binding energy of such a binary is released in the form of gravitational waves (GWs) in the last few seconds of the spiral-in phase before the formation of a black hole. In this article we investigate whether a fraction of this GW energy is transferred to magnetohydrodynamic waves in the magnetized plasma wind around the binary. Using the 3 + 1 orthonormal tedrad formalism, we study the propagation of a monochromatic, plane fronted, linearly polarized GW perpendicular to the ambient magnetic field in an ultra-relativistic wind, first in the comoving and then in the observer frame. A closed set of general relativistic magnetohydrodynamic (GRM) equations is derived in the form of conservation laws for electric charge, matter energy, momentum and magnetic energy densities. We linearize the GRM equations under the action of a monochromatic GW, which acts as a driver and find that fast magneto-acoustic waves grow, with amplitudes proportional to the GW amplitude and frequency and the strength of the background magnetic field.

Throughout Sects. 2–5, Gaussian geometrized units are adopted ($c = 1$) and Latin indices stand for 0, 1, 2, 3. In Sect. 6, however, the numerical results are given in SI units.

2. Covariant fluid equations

2.1. Electromagnetic field equations

Maxwell's equations in terms of the electromagnetic field tensors and the 4-current density $j^b_{\rm m} = (\tau, \boldsymbol{j})$ are:

$$\nabla_b F^{ab} = 4\pi j^a_{\rm m} \quad \text{and} \quad \nabla_b \mathcal{F}^{ab} = 0, \qquad (1)$$

where the covariant Faraday tensor F^{ab} and its dual $\mathcal{F}^{ab}$, can be decomposed into 4-vectors that, in the *rest frame* of an observer with 4-velocity u^a, reduce to the electric and magnetic field strengths, $E^a = (0, \boldsymbol{E})$ and $B^a = (0, \boldsymbol{B})$ (Lichnerowicz 1967):

$$\begin{aligned} F^{ab} &= u^a E^b - u^b E^a + \epsilon^{abcd} B_c u_d \ , \ \mathcal{F}^{ab} \equiv \tfrac{1}{2}\epsilon^{abcd} F_{cd}, \\ E^a &\equiv F^{ab} u_b \ , \ B^a \equiv \mathcal{F}^{ab} u_b. \end{aligned} \qquad (2)$$

In ideal MHD, the electric field vanishes in the rest frame of the plasma: $\boldsymbol{E} = 0$. Therefore $E^a \equiv F^{ab} u_b = 0$ in any frame and Faraday's tensor reduces to: $F^{ab} = \epsilon^{abcd} B_c u_d$.

3. Magnetohydrodynamics in the comoving frame

The physical situation we want to consider is that of a perfectly conducting, ideal plasma in the presence of a background magnetic field along the x-axis, perpendicular to the direction of GW propagation (Fig. 1). First we study the plasma rest-frame where: $\boldsymbol{B}^{(0)} = B_0 \boldsymbol{e}_x, \mu^{(0)} = \rho$ and $\boldsymbol{v}^{(0)} = \tau^{(0)} = p^{(0)} = j^{(0)}_{\rm m} = \boldsymbol{E}^{(0)} = 0$.

The effect of the GW is to induce small perturbations in all these quantities. Therefore, all equations will be linearized around the unperturbed state.

3.1. Maxwell's equations

The relevant, linearized Maxwell equations in the specified tedrad are (Marklund et al. 2000):

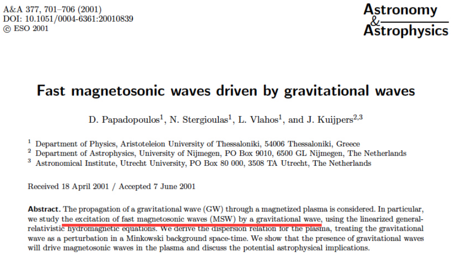
$$\nabla \times \boldsymbol{B}^{(1)} - \frac{\partial \boldsymbol{E}^{(1)}}{\partial t} = 4\pi \boldsymbol{j}^{(1)}_{\rm m} + \boldsymbol{j}^{(1)}_E, \qquad (4)$$

$$\nabla \times \boldsymbol{E}^{(1)} + \frac{\partial \boldsymbol{B}^{(1)}}{\partial t} = -\boldsymbol{j}^{(1)}_B, \qquad (5)$$

where the *gravitationally induced current densities* are just the collected Ricci rotation coefficients or GW-terms:

$$\boldsymbol{j}^{(1)}_{\rm E} \equiv -\frac{B_0}{2}\frac{\partial h^{(1)}}{\partial z}\boldsymbol{e}_y \quad \text{and} \quad \boldsymbol{j}^{(1)}_{\rm B} \equiv -\frac{B_0}{2}\frac{\partial h^{(1)}}{\partial t}\boldsymbol{e}_x. \qquad (6)$$

GW + B → EMW Magnetosonic



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Astronomy & Astrophysics

Fast magnetosonic waves driven by gravitational waves

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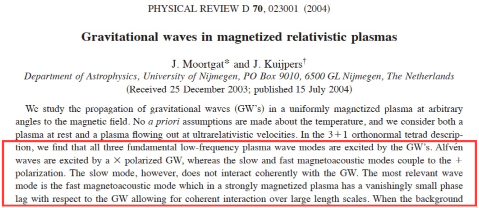
Abstract. The propagation of a gravitational wave (GW) through a magnetized plasma is considered. In particular, we study the excitation of fast magnetosonic waves (MSW) by a gravitational wave, using the linearized general-relativistic hydromagnetic equations. We derive the dispersion relation for the plasma, treating the gravitational wave as a perturbation in a Minkowski background space-time. We show that the presence of gravitational waves will drive magnetosonic waves in the plasma and discuss the potential astrophysical implications.



PHYSICAL REVIEW D **70**, 023001 (2004)

Gravitational waves in magnetized relativistic plasmas

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(Received 25 December 2003; published 15 July 2004)

We study the propagation of gravitational waves (GW's) in a uniformly magnetized plasma at arbitrary angles to the magnetic field. No *a priori* assumptions are made about the temperature, and we consider both a plasma at rest and a plasma flowing out at ultrarelativistic velocities. In the 3+1 orthonormal tetrad description, we find that all three fundamental low-frequency plasma wave modes are excited by the GW's. Alfvén waves are excited by a × polarized GW, whereas the slow and fast magnetoacoustic modes couple to the + polarization. The slow mode, however, does not interact coherently with the GW. The most relevant wave mode is the fast magnetoacoustic mode which in a strongly magnetized plasma has a vanishingly small phase lag with respect to the GW allowing for coherent interaction over large length scales. When the background

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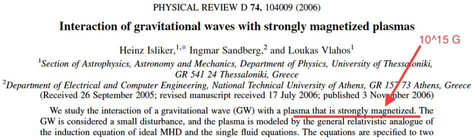

PHYSICAL REVIEW D **74**, 104009 (2006)

Interaction of gravitational waves with strongly magnetized plasmas

10^15 G

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(Received 26 September 2005; revised manuscript received 17 July 2006; published 3 November 2006)

We study the interaction of a gravitational wave (GW) with a plasma that is strongly magnetized. The GW is considered a small disturbance, and the plasma is modeled by the general relativistic analogue of the induction equation of ideal MHD and the single fluid equations. The equations are specified to two

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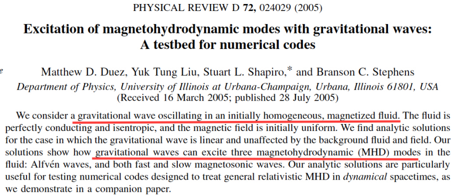

PHYSICAL REVIEW D **72**, 024029 (2005)

Excitation of magnetohydrodynamic modes with gravitational waves: A testbed for numerical codes

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(Received 16 March 2005; published 28 July 2005)

We consider a gravitational wave oscillating in an initially homogeneous, magnetized fluid. The fluid is perfectly conducting and isentropic, and the magnetic field is initially uniform. We find analytic solutions for the case in which the gravitational wave is linear and unaffected by the background fluid and field. Our solutions show how gravitational waves can excite three magnetohydrodynamic (MHD) modes in the fluid: Alfvén waves, and both fast and slow magnetosonic waves. Our analytic solutions are particularly useful for testing numerical codes designed to treat general relativistic MHD in *dynamical* spacetimes, as we demonstrate in a companion paper.

Vlasov Einstein system

$$p^\mu \frac{\partial f}{\partial x^\mu} - \Gamma^\mu{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial p^\mu} = 0 \quad \text{with} \quad g_{\mu\nu} p^\mu p^\nu = -m^2 c^2$$

$$\frac{\partial f}{\partial t} + \frac{p^j}{p^0}\frac{\partial f}{\partial x^j} - \frac{1}{p^0}\Gamma^j{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial p^j} = 0 \quad \text{on mass shell}$$

$$T^{\mu\nu} = c(-g)^{1/2} \int f\, p^\mu\, p^\nu \frac{dp^1\, dp^2\, dp^3}{-p^0}$$

$$n^\mu = (-g)^{1/2} \int f\, p^\mu \frac{dp^1\, dp^2\, dp^3}{-p^0}$$

Vlasov Einstein Maxwell system

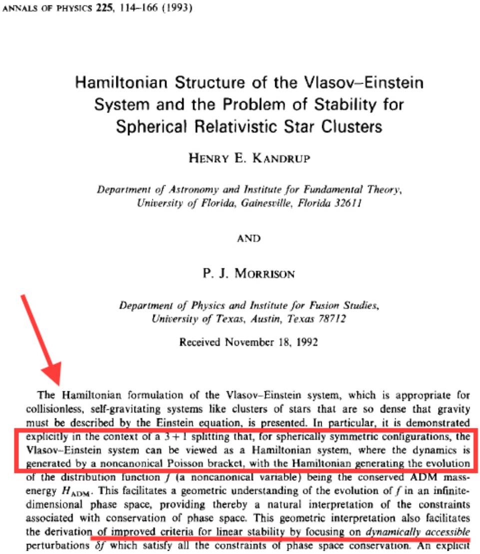
$$p^\mu \frac{\partial f}{\partial x^\mu} + (-\Gamma^\mu{}_{\alpha\beta}\, p^\alpha p^\beta + qF^\mu{}_\alpha p^\alpha)\,\frac{\partial f}{\partial p^\mu} = 0$$

$$\frac{\partial f}{\partial t} + \frac{p^j}{p^0}\frac{\partial f}{\partial x^j} + \frac{1}{p^0}(-\Gamma^j{}_{\alpha\beta}\, p^\alpha p^\beta + qF^j{}_\alpha p^\alpha)\,\frac{\partial f}{\partial p^j} = 0$$

$$j^\mu = q(-g)^{1/2}\int f\, p^\mu \frac{dp^1\, dp^2\, dp^3}{-p^0}$$

Should be reformulated in noncanonical Hamiltonian form (done by K.M. for EV). Casimirs.. stability etc.

Einstein Vlasov - Noncanonical Hamiltonian



ANNALS OF PHYSICS **225**, 114–166 (1993)

Hamiltonian Structure of the Vlasov–Einstein System and the Problem of Stability for Spherical Relativistic Star Clusters

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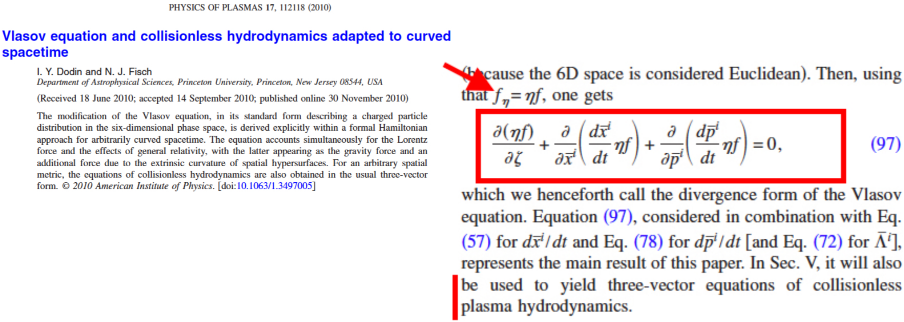
Received November 18, 1992

The Hamiltonian formulation of the Vlasov–Einstein system, which is appropriate for collisionless, self-gravitating systems like clusters of stars that are so dense that gravity must be described by the Einstein equation, is presented. In particular, it is demonstrated explicitly in the context of a $3+1$ splitting that, for spherically symmetric configurations, the Vlasov–Einstein system can be viewed as a Hamiltonian system, where the dynamics is generated by a noncanonical Poisson bracket, with the Hamiltonian generating the evolution of the distribution function f (a noncanonical variable) being the conserved ADM mass-energy H_{ADM}. This facilitates a geometric understanding of the evolution of f in an infinite-dimensional phase space, providing thereby a natural interpretation of the constraints associated with conservation of phase space. This geometric interpretation also facilitates the derivation of improved criteria for linear stability by focusing on *dynamically accessible* perturbations δf which satisfy all the constraints of phase space conservation. An explicit

Einstein Maxwell Vlasov system
3+1 separation, lapse function



PHYSICS OF PLASMAS **17**, 112118 (2010)

Vlasov equation and collisionless hydrodynamics adapted to curved spacetime

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(Received 18 June 2010; accepted 14 September 2010; published online 30 November 2010)

The modification of the Vlasov equation, in its standard form describing a charged particle distribution in the six-dimensional phase space, is derived explicitly within a formal Hamiltonian approach for arbitrarily curved spacetime. The equation accounts simultaneously for the Lorentz force and the effects of general relativity, with the latter appearing as the gravity force and an additional force due to the extrinsic curvature of spatial hypersurfaces. For an arbitrary spatial metric, the equations of collisionless hydrodynamics are also obtained in the usual three-vector form. © *2010 American Institute of Physics*. [doi:10.1063/1.3497005]

(because the 6D space is considered Euclidean). Then, using that $f_\eta = \eta f$, one gets

$$\boxed{\frac{\partial(\eta f)}{\partial \zeta} + \frac{\partial}{\partial \bar{x}^i}\left(\frac{d\bar{x}^i}{dt}\eta f\right) + \frac{\partial}{\partial \bar{p}^i}\left(\frac{d\bar{p}^i}{dt}\eta f\right) = 0,} \qquad (97)$$

which we henceforth call the divergence form of the Vlasov equation. Equation (97), considered in combination with Eq. (57) for $d\bar{x}^i/dt$ and Eq. (78) for $d\bar{p}^i/dt$ [and Eq. (72) for $\bar{\Lambda}^i$], represents the main result of this paper. In Sec. V, it will also be used to yield three-vector equations of collisionless plasma hydrodynamics.

$d/d\zeta$ is the ”time” partial derivative after intrducing the socalled ”lapse function”, defined in terms of the proper time of a fiducial observer, and a “shift vector” which is the rate at which the mesh in 3D space moves with respect to the fiducial observer. η is the determinant of the spatial part of the metric tensor.

EVM spherically symmetric equilibria

IOP Publishing — Classical and Quantum Gravity

Class. Quantum Grav. **26** (2009) 145003 (20pp) doi:10.1088/0264-9381/26/14/145003

A numerical investigation of the steady states of the spherically symmetric Einstein–Vlasov–Maxwell system

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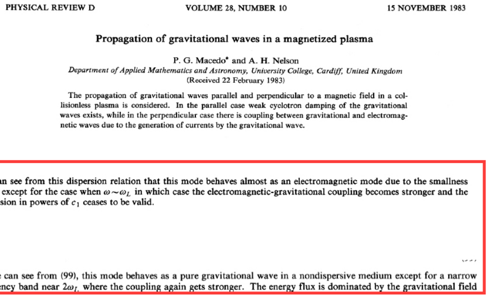
Abstract

We construct, by numerical means, static solutions of the spherically symmetric Einstein–Vlasov–Maxwell system and investigate various features of the solutions. This extends a previous investigation (Andréasson and Rein 2007 *Class. Quantum Grav.* **24** 1809) of the chargeless case. We study the possible shapes of the energy density profile as a function of the area radius when the electric charge of an individual particle is varied as a parameter. We find profiles which are multi-peaked, where the peaks are separated either by vacuum or a thin atmosphere, and we find that for a sufficiently large charge parameter the solutions break down at a finite radius. Furthermore, we investigate the inequality

$$\sqrt{M} \leqslant \frac{\sqrt{R}}{3} + \sqrt{\frac{R}{9} + \frac{Q^2}{3R}},$$

Vlasov dispersion relation



PHYSICAL REVIEW D VOLUME 28, NUMBER 10 15 NOVEMBER 1983

Propagation of gravitational waves in a magnetized plasma

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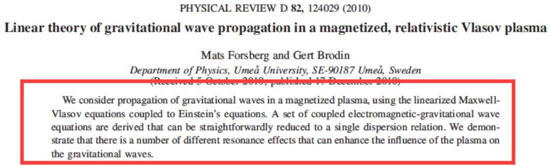
(Received 22 February 1983)

The propagation of gravitational waves parallel and perpendicular to a magnetic field in a collisionless plasma is considered. In the parallel case weak cyclotron damping of the gravitational waves exists, while in the perpendicular case there is coupling between gravitational and electromagnetic waves due to the generation of currents by the gravitational wave.

We can see from this dispersion relation that this mode behaves almost as an electromagnetic mode due to the smallness of c_1, except for the case when $\omega \sim \omega_L$ in which case the electromagnetic-gravitational coupling becomes stronger and the expansion in powers of c_1 ceases to be valid.

As we can see from (99), this mode behaves as a pure gravitational wave in a nondispersive medium except for a narrow frequency band near $2\omega_L$ where the coupling again gets stronger. The energy flux is dominated by the gravitational field



PHYSICAL REVIEW D **82**, 124029 (2010)

Linear theory of gravitational wave propagation in a magnetized, relativistic Vlasov plasma

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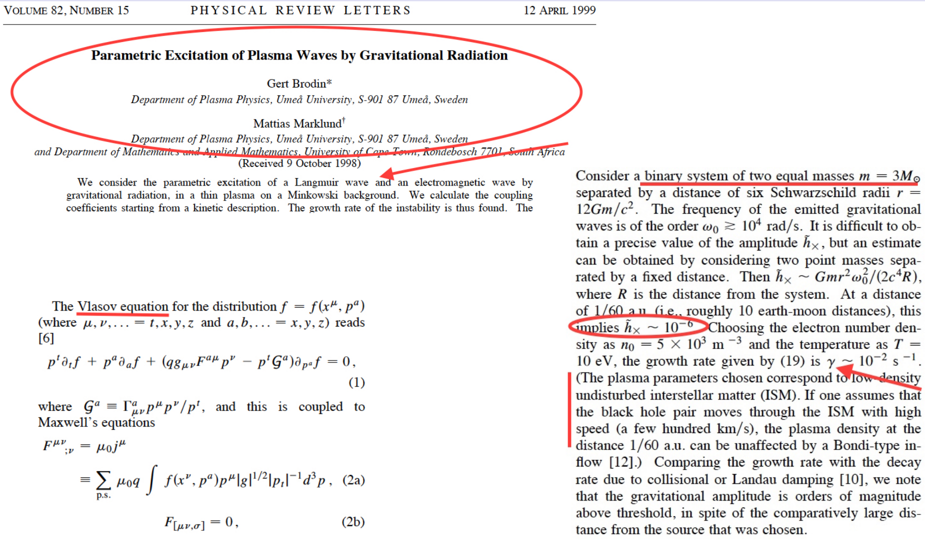
(Received 5 October 2010; published 17 December 2010)

We consider propagation of gravitational waves in a magnetized plasma, using the linearized Maxwell-Vlasov equations coupled to Einstein's equations. A set of coupled electromagnetic-gravitational wave equations are derived that can be straightforwardly reduced to a single dispersion relation. We demonstrate that there is a number of different resonance effects that can enhance the influence of the plasma on the gravitational waves.

Parametric processes: as in Raman scattering



VOLUME 82, NUMBER 15 PHYSICAL REVIEW LETTERS 12 APRIL 1999

Parametric Excitation of Plasma Waves by Gravitational Radiation

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(Received 9 October 1998)

We consider the parametric excitation of a Langmuir wave and an electromagnetic wave by gravitational radiation, in a thin plasma on a Minkowski background. We calculate the coupling coefficients starting from a kinetic description. The growth rate of the instability is thus found. The

The Vlasov equation for the distribution $f = f(x^\mu, p^a)$ (where $\mu, \nu, \ldots = t, x, y, z$ and $a, b, \ldots = x, y, z$) reads [6]

$$p^t \partial_t f + p^a \partial_a f + (q g_{\mu\nu} F^{a\mu} p^\nu - p^t \mathcal{G}^a) \partial_{p^a} f = 0 , \tag{1}$$

where $\mathcal{G}^a \equiv \Gamma^a_{\mu\nu} p^\mu p^\nu / p^t$, and this is coupled to Maxwell's equations

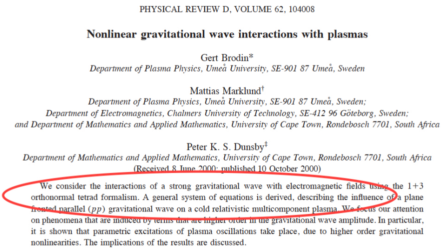
$$F^{\mu\nu}{}_{;\nu} = \mu_0 j^\mu$$

$$\equiv \sum_{\text{p.s.}} \mu_0 q \int f(x^\nu, p^a) p^\mu |g|^{1/2} |p_t|^{-1} d^3 p , \tag{2a}$$

$$F_{[\mu\nu,\sigma]} = 0 , \tag{2b}$$

Consider a binary system of two equal masses $m = 3M_\odot$ separated by a distance of six Schwarzschild radii $r = 12Gm/c^2$. The frequency of the emitted gravitational waves is of the order $\omega_0 \gtrsim 10^4$ rad/s. It is difficult to obtain a precise value of the amplitude $\tilde{h}_\times$, but an estimate can be obtained by considering two point masses separated by a fixed distance. Then $\tilde{h}_\times \sim Gmr^2\omega_0^2/(2c^4R)$, where R is the distance from the system. At a distance of 1/60 a.u. (i.e., roughly 10 earth-moon distances), this implies $\tilde{h}_\times \sim 10^{-6}$. Choosing the electron number density as $n_0 = 5 \times 10^3$ m $^{-3}$ and the temperature as $T = 10$ eV, the growth rate given by (19) is $\gamma \sim 10^{-2}$ s $^{-1}$. (The plasma parameters chosen correspond to low density undisturbed interstellar matter (ISM). If one assumes that the black hole pair moves through the ISM with high speed (a few hundred km/s), the plasma density at the distance 1/60 a.u. can be unaffected by a Bondi-type inflow [12].) Comparing the growth rate with the decay rate due to collisional or Landau damping [10], we note that the gravitational amplitude is orders of magnitude above threshold, in spite of the comparatively large distance from the source that was chosen.

Nonlinear parametric processes: wave-wave interactions



PHYSICAL REVIEW D, VOLUME 62, 104008

Nonlinear gravitational wave interactions with plasmas

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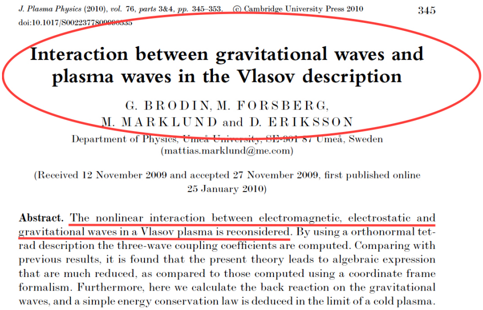
(Received 8 June 2000; published 10 October 2000)

We consider the interactions of a strong gravitational wave with electromagnetic fields using the 1+3 orthonormal tetrad formalism. A general system of equations is derived, describing the influence of a plane fronted parallel (*pp*) gravitational wave on a cold relativistic multicomponent plasma. We focus our attention on phenomena that are induced by terms that are higher order in the gravitational wave amplitude. In particular, it is shown that parametric excitations of plasma oscillations take place, due to higher order gravitational nonlinearities. The implications of the results are discussed.



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Interaction between gravitational waves and plasma waves in the Vlasov description

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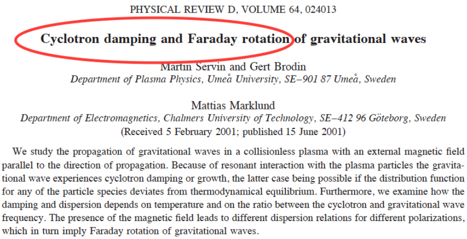
Abstract. The nonlinear interaction between electromagnetic, electrostatic and gravitational waves in a Vlasov plasma is reconsidered. By using a orthonormal tetrad description the three-wave coupling coefficients are computed. Comparing with previous results, it is found that the present theory leads to algebraic expression that are much reduced, as compared to those computed using a coordinate frame formalism. Furthermore, here we calculate the back reaction on the gravitational waves, and a simple energy conservation law is deduced in the limit of a cold plasma.

Perpendicular and parallel propagation



PHYSICAL REVIEW D, VOLUME 64, 024013

Cyclotron damping and Faraday rotation of gravitational waves

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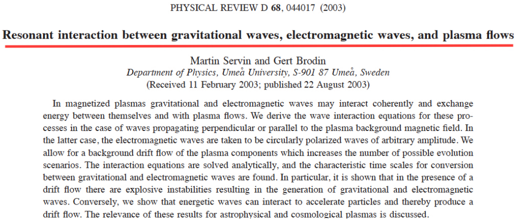
We study the propagation of gravitational waves in a collisionless plasma with an external magnetic field parallel to the direction of propagation. Because of resonant interaction with the plasma particles the gravitational wave experiences cyclotron damping or growth, the latter case being possible if the distribution function for any of the particle species deviates from thermodynamical equilibrium. Furthermore, we examine how the damping and dispersion depends on temperature and on the ratio between the cyclotron and gravitational wave frequency. The presence of the magnetic field leads to different dispersion relations for different polarizations, which in turn imply Faraday rotation of gravitational waves.



PHYSICAL REVIEW D **68**, 044017 (2003)

Resonant interaction between gravitational waves, electromagnetic waves, and plasma flows

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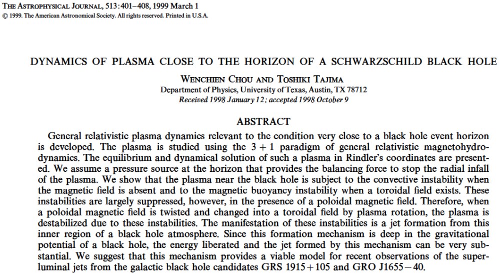
In magnetized plasmas gravitational and electromagnetic waves may interact coherently and exchange energy between themselves and with plasma flows. We derive the wave interaction equations for these processes in the case of waves propagating perpendicular or parallel to the plasma background magnetic field. In the latter case, the electromagnetic waves are taken to be circularly polarized waves of arbitrary amplitude. We allow for a background drift flow of the plasma components which increases the number of possible evolution scenarios. The interaction equations are solved analytically, and the characteristic time scales for conversion between gravitational and electromagnetic waves are found. In particular, it is shown that in the presence of a drift flow there are explosive instabilities resulting in the generation of gravitational and electromagnetic waves. Conversely, we show that energetic waves can interact to accelerate particles and thereby produce a drift flow. The relevance of these results for astrophysical and cosmological plasmas is discussed.

Plasmas and BH's



THE ASTROPHYSICAL JOURNAL, 513:401–408, 1999 March 1

DYNAMICS OF PLASMA CLOSE TO THE HORIZON OF A SCHWARZSCHILD BLACK HOLE

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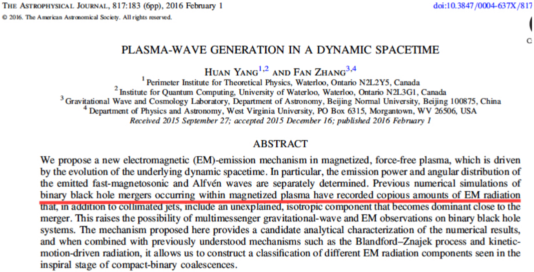
Received 1998 January 12; accepted 1998 October 9

ABSTRACT

General relativistic plasma dynamics relevant to the condition very close to a black hole event horizon is developed. The plasma is studied using the $3+1$ paradigm of general relativistic magnetohydrodynamics. The equilibrium and dynamical solution of such a plasma in Rindler's coordinates are presented. We assume a pressure source at the horizon that provides the balancing force to stop the radial infall of the plasma. We show that the plasma near the black hole is subject to the convective instability when the magnetic field is absent and to the magnetic buoyancy instability when a toroidal field exists. These instabilities are largely suppressed, however, in the presence of a poloidal magnetic field. Therefore, when a poloidal magnetic field is twisted and changed into a toroidal field by plasma rotation, the plasma is destabilized due to these instabilities. The manifestation of these instabilities is a jet formation from this inner region of a black hole atmosphere. Since this formation mechanism is deep in the gravitational potential of a black hole, the energy liberated and the jet formed by this mechanism can be very substantial. We suggest that this mechanism provides a viable model for recent observations of the superluminal jets from the galactic black hole candidates GRS 1915+105 and GRO J1655−40.



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PLASMA-WAVE GENERATION IN A DYNAMIC SPACETIME

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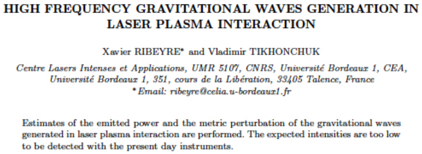
ABSTRACT

We propose a new electromagnetic (EM)-emission mechanism in magnetized, force-free plasma, which is driven by the evolution of the underlying dynamic spacetime. In particular, the emission power and angular distribution of the emitted fast-magnetosonic and Alfvén waves are separately determined. Previous numerical simulations of binary black hole mergers occurring within magnetized plasma have recorded copious amounts of EM radiation that, in addition to collimated jets, include an unexplained, isotropic component that becomes dominant close to the merger. This raises the possibility of multimessenger gravitational-wave and EM observations on binary black hole systems. The mechanism proposed here provides a candidate analytical characterization of the numerical results, and when combined with previously understood mechanisms such as the Blandford–Znajek process and kinetic-motion-driven radiation, it allows us to construct a classification of different EM radiation components seen in the inspiral stage of compact-binary coalescences.

GW's from laser plasma interactions



HIGH FREQUENCY GRAVITATIONAL WAVES GENERATION IN LASER PLASMA INTERACTION

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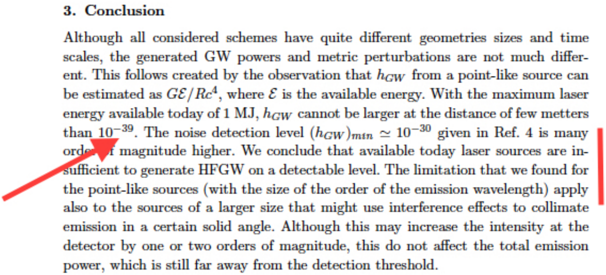
Estimates of the emitted power and the metric perturbation of the gravitational waves generated in laser plasma interaction are performed. The expected intensities are too low to be detected with the present day instruments.



3. Conclusion

Although all considered schemes have quite different geometries sizes and time scales, the generated GW powers and metric perturbations are not much different. This follows created by the observation that h_{GW} from a point-like source can be estimated as $G\mathcal{E}/Rc^4$, where $\mathcal{E}$ is the available energy. With the maximum laser energy available today of 1 MJ, h_{GW} cannot be larger at the distance of few metters than 10^{-39}. The noise detection level $(h_{GW})_{min} \simeq 10^{-30}$ given in Ref. 4 is many order of magnitude higher. We conclude that available today laser sources are insufficient to generate HFGW on a detectable level. The limitation that we found for the point-like sources (with the size of the order of the emission wavelength) apply also to the sources of a larger size that might use interference effects to collimate emission in a certain solid angle. Although this may increase the intensity at the detector by one or two orders of magnitude, this do not affect the total emission power, which is still far away from the detection threshold.

Then, in conclusion?

- The efficiency of conversion g.w. $\leftrightarrow$ e.m.w.in a magnetized vacuum (*Gertsenshtein* mechanism) is low but can be of interests for higly magnetized collapsed objects.
- There are several plasma mechanisms and resonances[3] that can enhance the coupling between gravitational and electromagnetic waves.

  Parametric processes appear to be of interest for a (Vlasov) plasma (in particular for relatively low frequency g.w. interacting with higher frequency e.m. waves).
- However it is not easy to estimate, under sufficiently general conditions, a realistic transformation efficiency between g.w.'s (in general time dependent gravitational fields) and e.m. waves in a plasma.

---

[3] Note: polarization effects $\leftrightarrow$ selection rules

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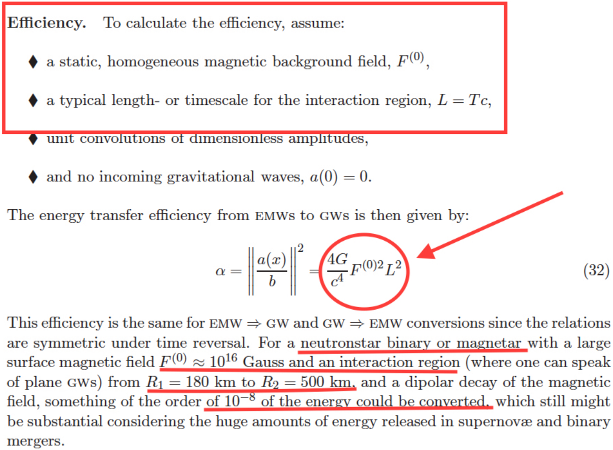
Efficiency in a vacuum magnetic field



Efficiency. To calculate the efficiency, assume:

- a static, homogeneous magnetic background field, $F^{(0)}$,
- a typical length- or timescale for the interaction region, $L = Tc$,
- unit convolutions of dimensionless amplitudes,
- and no incoming gravitational waves, $a(0) = 0$.

The energy transfer efficiency from EMWs to GWs is then given by:

$$\alpha = \left\|\frac{a(x)}{b}\right\|^2 = \frac{4G}{c^4} F^{(0)2} L^2 \tag{32}$$

This efficiency is the same for EMW ⇒ GW and GW ⇒ EMW conversions since the relations are symmetric under time reversal. For a neutronstar binary or magnetar with a large surface magnetic field $F^{(0)} \approx 10^{16}$ Gauss and an interaction region (where one can speak of plane GWs) from $R_1 = 180$ km to $R_2 = 500$ km, and a dipolar decay of the magnetic field, something of the order of 10^{-8} of the energy could be converted, which still might be substantial considering the huge amounts of energy released in supernovæ and binary mergers.

J. Moortgat: arXiv:gr-qc/0104006 - Essentially Gertsenshtein theory - 1960