Zhongguo Kuangye Daxue Xuebao
Journal of China University of Mining and Technology

2023 | Vol 28 | Issue 1 | Page 10-14
Journal Homepage: https://zkdx.ch/
DOI: 10.1654/zkdx.2023.28.1-3

Gravitational and Electromagnetic Relations with Proliferation of Waves in blood Plasma

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Abstract

The gravitational waves and electromagnetic waves are important as carriers of energy and information. This paper is deals with the study of the propagation and interaction of Gravitational waves in plasmas, with emphasis on nonlinear effects and applications within astrophysics. The physical systems are described by the Einstein-Maxwell-fluid equations or Einstein-Maxwell-Vlasov equations, when a kinetic treatment is required. The small amplitude and high-frequency approximation is employed for the gravitational waves, such that Perturbative techniques can be applied and space-time can be considered locally flat, with a gravitational radiation field superimposed on it. The gravitational waves give rise to coupling terms that have the structure of effective currents in the Maxwell equations and an effective gravitational force in the equation of motion for the plasma. The Einstein field equations describe the evolution of the gravitational waves, with the perturbed energy-momentum density of the plasma and the electromagnetic field as a source. The processes that are investigated are gravitational waves exciting electromagnetic waves in plasmas, altering the optical properties of plasmas and accelerating charged particles..

Keywords: Electromagnetic Waves in Plasma, Gravitational Wave, Electromagnetic Waves, Wave Interaction, Wave Propagation

1. Introduction

Waves can be found in Nature in many forms; waves on the ocean surface, acoustic waves from a beautiful music piece reaching your ear, ancient electromagnetic waves from a distant star etc. Virtually all physical systems sustain some kind of waves. They are important as carriers of energy and information from one place to another. In some physical systems waves play a central role in the dynamics. In other systems the waves are only a by-product, but may then be important as carriers of valuable information for us to study and thereby gain increased understanding of the nature of the system. The effects that determine the evolution of a wave can be broadly grouped as:

- Wave interactions • Propagation in varying backgrounds
- Nonlinear self-interactions
- Wave instabilities

Wave interactions are not restricted to waves of the the same kind, but can also occur between waves of very different types. A striking example is the coupling between low-frequency waves in the earth's crust during earthquakes and electromagnetic waves in the ionosphere surrounding our planet. This can sometimes be observed as an illumination of the sky during an earthquake. Actually, it has been speculated whether observations of specific changes in the ionosphere can be a used to predict earthquakes. Waves may also interact directly with particles. A surfer (viewed as a particle) riding an ocean wave is such an example. The wave pushes (with the aid if gravity) the surfer forward, whereby the surfers velocity is increased. In so doing, some amount of energy is converted from wave energy to kinetic (particle) energy. If the number of particles (surfers) interacting with the wave is large, the interaction may lead to rapid damping of the wave and the particle system is "heated". The properties of a wave, such as speed, direction of propagation, energy, polarization etc, depends on the background in which it propagates. A background that varies in time and/or space leads to variations in these properties. This is what "bends" light rays in a piece of glass and makes the stars "twinkle" (or scintillate). The background in which the starlight propagates (e.g. the Earth's atmosphere) fluctuates randomly, causing random variations in the intensity of the light. Nonlinear self-interaction of waves can be understood as follows. If a wave is powerful enough, it can affect the background in which it propagates. Since the evolution of the wave depends on the background, the wave thereby interacts with itself. For instance, a light beam may affect the background to make it behave like a focusing lens. As the light beam gets focused, the light intensity increases, leading to even larger effect on the background, i.e. stronger focusing, etc. The result is that the light beam "collapses" into a narrow region with high energy density. Waves also function as a mathematical tool for investigating the stability of physical systems. By studying the equations that describe the surface of a lake, it is clear that it is a mathematically valid solution to have a surface as smooth as a mirror even on a windy day. If one, however, adds a very small perturbation (a small waveripple) to that solution one finds that the solution is unstable; the wind causes the small waves to grow larger. The conclusion is that — since there are always some very small wave-like irregularities even on a ”mirror-smooth” surface — if there is wind there will also be surface waves. This is an example of a wave instability. This paper is deals with study of gravitational and electromagnetic waves in plasmas, with main focus on how these waves can interact and on their propagation properties.

2. Gravitational and Electromagnetic Waves in Plasmas

Gravitational waves are predicted to exist by the theory of general relativity but have, in the writing of this thesis, not yet been observed directly. Still, very few physicists doubt their existence. The reason is that general relativity has been very successful in explaining gravity; in the solar system, in astronomy and astrophysics, and in the evolution of the entire Universe starting with the Big Bang. If gravitational waves do not exist, the mentioned effects must be explained by a theory significantly different than relativity theory, and for this, there are no good candidates. The laws of 3 gravity that were written down by Isaac Newton in 1687 is a good description of most gravitational effects that occur on earth and in the solar system. In Newtonian gravity, massive objects act on each others with gravitational forces, according to Newtons laws. In general relativity, there are no gravitational forces. Gravity is described as curvature of space-time. In particular, a massive object (e.g. a star) curves the space-time. A light particle (e.g. a planet) tends to fall towards, or orbit, a more massive object. The explanation is, simply, that this is how objects move in curved space-time — not by being caused by a force acting on it, as in Newtonian theory. Space time is, however, not just an arena for objects to exist and interact in. It is in itself a dynamical object that possess energy, momentum and angular momentum. Gravitational waves can be described as ripples in the space time curvature. They propagate with the velocity of light in vacuum and carry energy, momentum and angular momentum, that can be transferred to particles and electromagnetic fields. In 1975, R. Hulse and J. Taylor reported on the discovery of a binary star system (PSR 1913+16) that came to provide the so far strongest observational evidence for gravitational waves

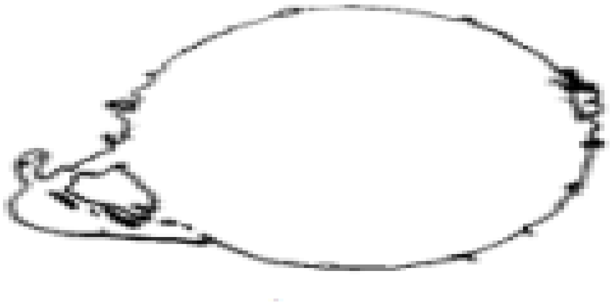
[1]. The two stars in the binary pulsar evolve around a common center of mass and have velocities as large as 0.1 percent of the speed of light. Observations show that the system loses energy — presumably by radiating gravitational waves — at precisely the rate predicted by relativity theory. There has been attempts since the 1960s to directly detect gravitational waves in earth-based laboratories, and the search intensified with the finding of the Hulse-Taylor pulsar. It is well understood why these attempts have so far been unable to register any gravitational waves. The reason is that gravitational waves interact very weakly with matter and the natural noise that exists in any detector (thermal vibrations, sound waves from the surroundings and even seismic disturbances) has typically a larger effect on the detector equipment than the gravitational waves. The technology has, however, progressed steadily and at the present time it is believed that current technology can reduce the noise and amplify the signal to a level where gravitational wave detection should be possible. One of the most promising detectors is LIGO

[2], basically consisting of a system of laser beams and mirrors, that has been running since 2002 with continuously increasing sensitivity. The europeen detectors GEO600

[3] (technically less advanced) and VIRGO

[4] (not yet in operation) uses the same technique. The detectors will later function as gravitational wave ”telescopes”. Astronomy today does not record only the visible light that reaches earth from cosmos. During the last decades a number of new ”windows to the universe” has been opened. These new windows consists of studying cosmic radio waves, micro waves, gamma rays, neutrinos etc. Each time a new observational window have been opened, astronomers have found new types of objects in space and learned of new Astrophyscial and cosmological processes. Most likely, the ”gravitational wave window” will be no exception. Gravitational wave astronomy is particularly interesting since gravitational waves are able to penetrate most barriers that hinder electromagnetic waves and particle rays from reaching our telescopes.

To make sense of the images that will come from gravitational wave telescopes, it must first be understood how gravitational waves are produced and how they evolve as they propagate through space. Some waves are too weak to ever be detected on (or nearby) earth. They may, however, interact with matter and electromagnetic fields, as illustrated in and thereby give rise to secondary effects that potentially can be observed. In extremely energetic processes, such as supernovae explosions, gravitational waves interact more strongly and may be an important part of the dynamics. The interaction may also affect the gravitational wave and thus alter the form of the wave signals expected to reach the detectors. The common state of matter in these scenarios is the plasma state. A plasma is a collection of positively and negatively charged particles. This is the state that ordinary matter turns into if heated sufficiently, so that its molecular and atomic structure is disrupted. The plasma state remains as long as the kinetic energy of the particles is significantly larger than the attractive binding energy. At an early stage the entire universe was in a plasma state (except for the dark matter, possibly). In present time, the plasma state is still very common; stars are made of plasma and the ”empty” space between stars and galaxies is filled with a dilute plasma. Plasma physics has been stimulated mostly by the strive to understand the sun the earths magnetosphere and to construct fusion reactors. In many aspects a plasma behave like a fluid with electromagnetic properties. What distinguishes plasmas is the occurrence of collective behaviour and the variety of nonlinear effects. Collective behaviour is a result of the long-range electromagnetic interaction force, that tends to make particles move in a coordinated way. The nonlinearities leads to that motion and electromagnetic fields in plasmas tend to amplify each others (or their self, for that matter). Needless to say, perhaps, is that the behaviour of plasmas is in general rather complex and difficult to analyse. Much insight into the nature of plasmas can be gained, however, by studying the many type of wave phenomena that occur in plasmas.



In plasmas one can find familiar wave types, like ”ordinary” electromagnetic waves and sound waves, but also waves that have no counterpart in other medias, and it is no exception in plasma physics, that the waves are important as carriers of energy and information.

2. General Relativistic Plasma

General relativistic plasma physics is the interplay between space-time geometry, electromagnetic fields and matter that is in a plasma state. Each of these subfields have been well studied for, at least, almost a century. Still, this field is to a large extent unexplored, even though plasma is often the relevant state of matter where general relativistic effects are important. This is mainly because that both general relativity theory and plasma physics are both complex and highly nonlinear theories. To compensate for these difficulties, one often uses simplified models, e.g. simple matter models, like neutral ideal fluids. In many cases such simplifications are well justified, e.g. the gravitational coupling between two stars is not very sensitive to the internal structure of the stars. Describing the stars by ideal neutral fluids, or even as point particles, gives in many cases a sufficiently accurate result. In traditional plasma physics, the gravitational field from the plasma itself is usually discarded, since many electromagnetic effects dominate over gravitational effects. The occurrence of gravitational fields is usually due to some external source, e.g. a planet or a “neutral star”, and is described by Newton’s gravitational law.

3. Gravitational Waves

The following quotation is from a letter, written in 1936, from Albert Einstein to Max Born ”Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to first approximation.” It is a remarkable statement since gravitational radiation was one of the first predictions (published in 1916 of Einstein’s general theory of relativity. But the prediction from 1916 was made for linear gravitational waves, i.e. a result of perturbation theory — which sometimes do fail. Later Einstein attempted to find exact wave solutions to the field equations, but the nonlinearities in the equations made it very difficult to find such solutions that are free from singularities. This lead him, and others, to believe that gravitational radiation is not a possibility. Although Einstein (and others) soon realized that the singularities where not as severe as they first seemed — and he returned to the belief that gravitational waves indeed could exist — gravitational waves remained a controverse until the 1970s. There are mainly two reasons for this. Firstly, even though the field equations implies that time-varying mass-quadrupole moments (such as binary stars). emit gravitational waves, there was no sign of radiation reaction (change in energy and angular momentum) in the equation of motion for the source. The second reason is that the energy density carried by gravitational waves can, at any space-time point, be made zero by choosing a particular set of coordinates. The relativity community could not at that time agree on the meaning of this, i.e. if this means that gravitational waves are not real. But in the 1970s the reaction problem was finally well understood (for a review, see [34, 35]). Suitable formalisms for studying the equation of motion for binary stars had been found — the radiation reaction a raises first at fifth order in the post-Newtonian perturbation expansion.

The discovery of the Hulse Taylor binary pulsar in 1975, which looses energy at the predicted rate, came to provide the first observational evidence of gravitational waves. Still, the observed energy loss of the Hulse-Taylor pulsar can only be considered as an indirect observation of gravitational waves. The last decades, there has been much effort in designing detectors for direct observations of gravitational waves. These consist of large metal bars or spheres , or systems of lasers and mirrors — as isolated from external and internal noise as current technology allows. It is believed that these detectors have now reached the level of sensitivity where it should be possible to detect some of the gravitational radiation bursts that Earth is occasionally exposed to, and the sensitivity is increased continuously. The rate of those events that should be possible to detect today are, however, expected to be low. Currently, the detector signals consist of what seem to be noise. Still, gravitational wave evidence may be hidden in these signals, which are analysed closely and compared to signals from other detectors. The analysis relies crucially on what the expected gravitational wave forms are. Although the first objective is to find evidence of gravitational radiation and thereby confirm this implication of general relativity, it is the next step that scientists find most exciting. The detectors will then function as gravitational wave ”telescopes”, see e.g. the review by Schutz. Gravitational radiation can penetrate most barriers that hinder conventional radiation from reaching earth. Gravitational wave telescopes will therefore open up a new window into space, through which scientist may be able to observe so far hidden regions, such as the interior of supernova explosions, emissions from neutron stars and black holes or the Big Bang. Another important feature is that gravitational waves come from the bulk motion of their sources, whereas most electromagnetic waves that are observed resides from individual particles. The most important sources of gravitational waves are considered.

4. Electromagnetic Waves

In this paper, electromagnetic waves refer to waves in plasmas with E, B 6= 0. This includes, besides waves that resemble electromagnetic waves in vacuum, also low-frequency waves in magnetized plasmas, such as Alfven waves. In cosmological and astrophysical plasmas, electromagnetic waves is the main carrier of information. Many astrophysical plasmas, such as stars and interstellar plasmas, are well described by magnet hydro dynamics, where the electromagnetic waves are also very important in the dynamical processes. In laboratory plasmas, electromagnetic waves are for example applied for heating of fusion plasmas, as a diagnostic tool and to accelerate particles. Trough out this section, we discard gravitational fields. Most gravitational wave sources, e.g. compact binaries, are also associated with strongly curved background space-times, like the Schwarz child space time. In general, it is difficult to distinguish the wave from the background. If the wavelength is much smaller than the characteristic length-scale of the background curvature, however, this distinction simplifies. This is referred to as the high-frequency approximation, for which Isaacson presented a formalism, where gravitational waves in curved space-time can be treated in a perturbative manor (up to third order in wave amplitude) . The idea, illustrated in is that in the limit of high frequencies, the background does not vary over distances comparable to the wavelength. By a coordinate transformation, the background space-time can then be made flat in any region of this size. When propagating over distances comparable to the background length scale, the background curvature makes the waves follow null geodesics and be ”deflected”, just like light rays. By taking into account higher order terms in the high-frequency approximation, the dispersion of gravitational waves by the background curvature is found.

5. Conclusion

Gravitational wave energy can be transferred to a plasma by exciting waves in the plasma. The process is most efficient if it is resonant. This can be analysed using the three-wave interaction formalism. In this paper, the decay of gravitational waves to magneto hydrodynamic waves through three-wave interaction is considered. As a first step a magneto hydrodynamic plasma model that takes space-time curvature into account is derived. The space-time is then taken to be that of linear gravitational waves in Minkowski space. The gravitational waves are assumed to propagate parallel to the plasma background magnetic field and the coupling to magneto hydrodynamic waves with arbitrary direction of propagation is considered. Coupled mode equations, that describe the evolution of the wave amplitudes due to three-wave interaction, are derived. The equations are shown to be energy conserving and fulfill the Manley-Rowe relations. Particular attention is paid to the case when the gravitational wave act as pump wave — having constant amplitude on the time scale of interest. In this case the magneto hydrodynamic waves undergo parametric excitation and their amplitudes grow exponentially in time, with the growth rateΓ= SQRT(CIC∗ II h), where CI and CII are the coupling coefficients, appearing in the coupled mode equations, and h is the gravitational wave amplitude. In an idealized model of a magnetized plasma close to a compact binary, the exponential growth rate becomesΓ∼ 10 −2 s −1 .

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