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The planetary–exoplanetary environment: A nonlinear perspective

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Abstract

A review of the fundamental physical processes in the planetary–exoplanetary environment is presented, with emphasis on nonlinear phenomena. First, we discuss briefly the detection of exoplanets and search for radio emissions from exoplanets. Next, we give an overview of the concepts of waves, instabilities, chaos and turbulence in the planetary–exoplanetary environment based on our present knowledge of the solar-terrestrial environment. We conclude by discussing cyclotron masers and chaos in nonthermal radio emissions in the planetary–exoplanetary environment.

Keywords: Plasmas; Radio emissions; Nonlinear dynamics; Planets; Exoplanets

1. Introduction

The planetary–exoplanetary environment refers to the regions of planetary and exoplanetary atmosphere, ionosphere and magnetosphere, which are influenced by the physical conditions in solar and extra-solar stellar wind, respectively. The progress of research on planet–exoplanet has accelerated significantly in the past years. The planetary environment in the solar system has been explored *in situ* by a large number of spacecraft and analyzed extensively by ground-based observations. These experimental observations have been verified in detail by analytical theory and numerical simulations. Our knowledge of the physical processes occurring in the nearby planetary environment (Chian and Kamide, 2007; Kamide and Chian, 2007) provides the basic tools for our investigation of the complex physical processes taking place in the distant exoplanetary environment in extra-solar systems. The recent discovery of exoplanets has contributed to a fast growing interest in the study of the planetary–exoplanetary environment.

The planetary magnetospheres of the solar system come in many forms and sizes (Kivelson, 2007). A comparative study of planets helps us to reconstruct the past history and predict the future evolution of the Earth. Planetary science allows us to contrast the properties of the Earth's environment with the environment of other planets, to reveal how planetary magnetospheric-ionospheric-atmospheric processes respond to changes of planetary scale and rotation rate and of solar wind structure in the vicinity of the planet.

The study of exoplanets in extra-solar systems is one of the priority areas of space science research today. It aims to discover Earth-like exoplanets, and to search for signs of habitability and evidence of biosignatures. One of the fundamental requirements for the planet habitability is the existence of a planetary magnetosphere and a planetary

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atmosphere. The Earth's magnetosphere and atmosphere prevent harmful galactic cosmic rays from reaching the Earth's surface, without which human life may be in jeopardy. It is natural to expect that the exoplanetary environment exhibits a huge diversity of dynamics and structures.

The interaction of solar–stellar wind with planetary–exoplanetary magnetosphere leads to energetic electrons resulting from magnetic reconnections in the planetary–exoplanetary environment, with the consequent emission of nonthermal planetary–exoplanetary radio waves. A variety of intense nonthermal planetary radio emissions are known in the solar system, e.g., the auroral radio emissions from Earth, Jupiter, Saturn, Uranus and Neptune, and the radio bursts from the Io–Jupiter flux tube (Chian, 1993; Zarka, 1998, 2004; Treumann, 2006). The former is thought to be driven by the solar wind flow pressure or energy flux on the magnetospheric cross-section, while the latter is a product of the Io–Jupiter electrodynamic interaction. Many articles (e.g., Zarka, 1998; Zarka et al., 2001) examined the possibility of radio emissions from exoplanets and concluded that 'hot Jupiters', if magnetized, might emit strong radio emissions detectable by large ground-based low-frequency antenna arrays.

The planetary–exoplanetary environment behaves as a complex system governed by a rich variety of nonlinear phenomena, which appear for example in magnetic reconnections (Valdivia et al., 2003, 2005, 2006) and nonthermal radio emissions (Chian et al., 1994, 2000; Chian and Abalde, 1995). The aim of this paper is to present a brief review of the planetary–exoplanetary environment from a nonlinear perspective, exemplified by nonthermal radio emissions from planets and exoplanets. In Section 2, we discuss the detection of exoplanets and search for radio emissions from exoplanets. In Section 3, we discuss the basic concepts of waves, instabilities, chaos and turbulence in the planetary–exoplanetary environment. In Sections 4 and 5, we discuss cyclotron masers and chaos in nonthermal radio emissions in the planetary–exoplanetary environment, respectively. A conclusion is given in Section 6.

2. Exoplanets

2.1. Detection of exoplanets

The recent discovery of exoplanets led to a rapid advance in the theoretical understanding of stellar and planetary formation and the implementation of dedicated observational programs of exoplanets. The first exoplanet was detected around a neutron star, the millisecond radio pulsar PSR B1257+12, using the Arecibo radiotelescope (Wolszczan and Frail, 1992). The first exoplanet around a solar-type (main sequence) star, 51 Pegasi, was detected by Mayor and Queloz (1995). Since the 1990s, a steadily increasing number of exoplanets have been observed.

Exoplanets can be detected by different techniques: timing, radial velocity, transit, microlensing, and direct imaging (Marcy and Butler, 1998; Perryman, 2000; Bodenheimer and Lin, 2002). The motion of an exoplanet in a circular orbit around a host star causes the star to undergo a reflex circular motion about the star–planet barycenter, resulting in the periodic perturbation of the arrival time, radial velocity and astrometric position of some periodic reference signal. The first detection of an exoplanet was made from precise measurements of the periodic fluctuations in the arrival times of radio pulses from a pulsar, caused by gravitational perturbations due to the planets (Wolszczan and Frail, 1992). Most exoplanets around the main sequence stars have been detected using the radial velocity technique. The periodic transit of a planet (indicated by eclipse) across the face of the host star provides the photometric diagnostic of an exoplanet. The COROT satellite used the transit technique to discover a small planet, COROT-Exo-7b, with diameter less than twice of the Earth radius which orbits a Sun-like star (ESA, 2009). Departures from symmetry in the light curve of a gravitationally lensed star can be used to detect an exoplanet. Protoplanetary disks, which represent an early evolutionary stage of planetary formation, are being imaged from space. Direct imaging of exoplanets from the light reflected off the host star may be viable if higher resolution and lower noise imaging techniques are developed.

The ongoing efforts in the exoplanetary science are directed towards the development of infrared interferometry, the detection of Earth-like planets and measurement of their spectral characteristics, as well as search for exoplanetary radio emissions. Theoretical atmospheric models of exoplanets provide predictions of exoplanetary temperatures, radii, albedos, chemical condensates and spectral features as a function of mass, composition and distance from the host star. Emphasis is to find exoplanets occupying the 'habitable zone' in which liquid water may be present, and to search for the signatures of the presence of life.

2.2. Search for radio emissions from exoplanets

The discovery of exoplanets has stimulated the search for radio emissions coming from these objects. Observational search for radio emissions from exoplanets based on existing large low-frequency radio telescopes were conducted using the Very Large Array (VLA) at 74 MHz, 333 MHz and 1.4 GHz (Winglee et al., 1986; Bastian et al., 2000; Lazio et al., 2004; Lazio and Farrell, 2007), the Ukrainian T-shape Radiotelescope (UTR-2) below 32 MHz (Zarka et al., 1997; Ryabov et al., 2004), and the Giant Metrewave Radio Telescope (GMRT) at 150 MHz (Winterhalter et al., 2006; George and Stevens, 2007). No radio signal from exoplanets has been detected so far. The success of future detection depends on the existence of exoplanetary radio emissions much more intense than Jovian radio emissions at frequencies higher than the Earth's ionospheric cutoff of around 10–20 MHz, as well as a better understanding of the physical conditions of the host-stellar and exoplanetary environment.

A large fraction of the exoplanets discovered up to date have a semi-major axis less than 0.1 AU. These planets are called 'hot Jupiters' because of their strong irradiation, possibly resulting from the intense interactions with their close-in host stars. Observational and theoretical studies of star–planet interactions can probe the magnetic activities of host stars of exoplanets, which may assist the search for exoplanetary radio emissions. Stevens (2005) analyzed the expected radio emission from a sample of nearby extra-solar giant planets. Based on recent results on the correlation between stellar X-ray flux and mass-loss rates from nearby stars, the expected stellar wind properties of the host stars are estimated, which were used to propose five most promising exoplanets for detecting radio emissions. Gu et al. (2005) presented a model and Shkolnik et al. (2008) reported the observation of the chromospheric activity of several stars with hot Jupiters and obtained evidence of synchronicity of chromospheric line emissions of a number of stars with its planet's orbit; this on-off nature of star–planet interaction is suggestive of magnetic interaction between a star and its hot Jupiters. Preusse et al. (2007) performed three-dimensional numerical simulation of the interaction between the stellar wind with the exoplanetary magnetosphere based on resistive magnetohydrodynamic (MHD) equations, and studied the development of a magnetic field-aligned current system analogous to the Jupiter–Io scenario. In particular, they were able to reproduce the angles observed by Shkolnik et al. (2008) with a model. Zarka (2007) studied the plasma interactions of hot Jupiters with their host stars and concluded that the primary engine for driving exoplanetary radio emissions is the interaction of a plasma flow with an obstacle in the presence of a strong magnetic field.

An accurate prediction of maximum emission frequency and radio fluxes are essential to identify the most promising exoplanetary targets for future search. The first prediction study was carried out by Zarka et al. (1997). Farrell et al. (1999) applied the radiometric Bodes law of radio power generation to a number of hot Jupiters and inferred that τ Boo is a good candidate for stellar wind-driven cyclotron maser. Lazio et al. (2004) presented the first catalog of the estimate for radio emissions of a large number of exoplanets, by considering the effect of kinetic energy of stellar wind. The influence of stellar coronal mass ejections on exoplanetary radio emission was studied by Grießmeier et al. (2006). Grießmeier et al. (2007a) concluded that in the estimate of exoplanetary radio fluxes it is necessary to taking into account the stellar mass, radius or age, and suggested that the search of exoplanetary radio emissions should target young and flaring stars where frequent Coronal Mass Ejections (CMEs)-like events are expected. Grießmeier et al. (2007b) refined estimations of exoplanetary radio emissions, including exoplanetary dipole moments, for a large list of targets by comparing four different (magnetic energy, kinetic energy, CME and unipolar interaction) models.

It is worth mentioning that the molecular line emission at radio wavelengths is a useful tool to detect the existence of life in the outer space. Amino acids, the building blocks of proteins and therefore key ingredients for the origin of life, have been found in meteorites on the Earth but have not yet been directly observed in the interstellar space. A team of radio astronomers reported the first detection of an organic molecule – amino acetonitrile – a chemical precursor of glycine (the simplest amino acid) in the Large Molecule Heimat, a giant molecular cloud in the star-forming region Sagittarius B2(N) near the center of Milky Way (Belloche et al., 2008). This millimeter observation was carried out with the IRAM Plateau de Bure Interferometer and the IRAM 30 m telescope in Spain, the Australia Telescope Compact Array, and the NRAO Very Large Array. In contrast to the magnetospheric radio emissions discussed in the previous paragraphs which emit in the frequency range of tens to hundreds of MHz, the molecular line emissions detected by Belloche et al. (2008) emit at a much high-frequency range of tens to hundreds of GHz. This finding provides evidence that the precursor organic molecules essential for the origin of life can be found in the interstellar space. Most star-forming regions are expected to be rich in planetary formation. In fact, an exoplanet has been detected in the circumstellar accretion disks of a young star AB Aurigae in the star-forming region Tarus-Auriga (Oppenheimer et al., 2008).

3. Complex nature of the planetary–exoplanetary environment

The planetary–exoplanetary environment consists of fully ionized plasmas (stars, stellar winds, planetary magnetospheres), partially ionized plasmas (planetary ionospheres), and neutral fluids (planetary atmospheres). The star–planet relation depends on a chain of coupling processes involving the stellar interior–stellar atmosphere–stellar wind–planetary bow shock–planetary magnetosphere–planetary ionosphere–planetary atmosphere interactions. The planetary–exoplanetary environment is complex by nature dominated by waves, instabilities and turbulence. The nature of stellar–planetary environment can be studied by theoretical analysis, laboratory, ground, and space observations, as well as computer simulations. In this section, we review the basic concepts of waves, instabilities and turbulence in the planetary–exoplanetary environment (Baumjohann and Treumann, 1996; Treumann and Baumjohann, 1997; Jatenco-Pereira et al., 2005; Kamide and Chian, 2007).

3.1. Linear waves

Disturbances in fluids and plasmas propagate as waves which transport the energy of perturbations from one region to another. A wave is characterized by its amplitude and phase (frequency and wavenumber). If the amplitude of the disturbances is small, linear waves can be represented as a superposition of plane waves using Fourier analysis. In a dispersive medium such as a plasma, wave propagation follows a dispersion relation between wave frequency and wavenumber. The velocity of wave phase propagation is called phase velocity; the velocity of wave energy flow is called group velocity. In general, the phase and group velocities of a wave are different in a dispersive medium.

Two types of waves can propagate in a plasma. The first type is electromagnetic waves which reduce to light waves in a vacuum; examples of electromagnetic waves in magnetized plasmas are whistler and Alfvén waves. Whistlers are high-frequency right-hand circularly polarized electromagnetic waves which can be excited by a lightning in one hemisphere and travel to the other hemisphere along the planetary magnetic field lines through the magnetosphere. Due to the wave dispersion of whistler waves, higher-frequency waves have higher group and phase velocities, thus whistlers will be detected in a frequency–time sonogram as a falling tone. Whistlers are observed in the Earth's magnetosphere during substorms as well. They can also be induced by planetary atmospheric lightnings. Shear Alfvén waves are low-frequency electromagnetic waves propagating parallel to the ambient magnetic field that represent string-like oscillations of the ambient magnetic field. Alfvén waves are observed in the solar atmosphere, solar wind, and planetary magnetospheres.

The second type is plasma waves which are internal plasma oscillations; examples of plasma waves are Langmuir waves and ion-acoustic waves. Langmuir waves are high-frequency electron plasma waves with frequency close to the plasma frequency (which is a function of the plasma density). They are related to the oscillatory motion of the electrons driven by the electrostatic force that restores charge neutrality in plasmas. Langmuir waves are observed in solar wind in connection with type-III solar radio emissions, in planetary auroral plasmas, and upstream of planetary bow shocks, interplanetary shocks and the heliosphere's termination shock. Ion-acoustic waves are low-frequency ion plasma oscillations related to the oscillatory motion of ions, which have similar properties as sound waves in a gaseous medium. Ion-acoustic waves are observed in solar wind, upstream and downstream of planetary bow shocks and interplanetary shocks, and planetary ionospheres.

A cut-off of a wave occurs in a plasma when the wavenumber vanishes, leading to wave reflection. In an unmagnetized plasma, the cut-off frequency of an electromagnetic wave is the plasma frequency; hence, an electromagnetic wave can only propagate above the plasma frequency. The ionosonde technique used for determining the density profile of the ionosphere is based on the reflection of a radio wave at a critical layer of the ionosphere due to wave cut-off. Resonance of a wave occurs when the wavenumber becomes infinite, leading to wave absorption. For an electromagnetic wave propagating along the ambient magnetic field, a resonance occurs at the electron cyclotron frequency for a right-hand circularly polarized electron–cyclotron wave, and a resonance occurs at the ion–cyclotron frequency for a left-hand circularly polarized ion–cyclotron wave. These resonances lead to wave–particle interactions and wave damping or wave growth. Whistlers can accelerate electrons in the magnetosphere to relativistic energies via the electron cyclotron resonance.

Wave damping can be caused by collisional or collisionless processes. Collisional wave dissipation is due to binary collisions between either charged or neutral particles. Examples of collisionless wave dissipation are Landau damping and cyclotron damping associated with wave–particle interactions. Landau damping occurs when the particle velocities are close to the phase velocity of a plasma wave. Cyclotron damping occurs when the particle velocities parallel to the ambient magnetic field are close to the wave phase velocities parallel to the ambient magnetic field, Doppler-shifted by the cyclotron frequencies of either electrons or ions, depending on the wave polarization. Landau-damping and cyclotron damping are important mechanisms for waves to heat and accelerate astrophysical plasmas.

3.2. Instabilities

In general, the planetary–exoplanetary environment is in a non-equilibrium state due to a variety of instabilities that occur in plasmas and fluids. Instabilities in plasmas and atmospheres are driven by a multitude of free energy sources such as velocity shear, gravity, temperature anisotropy, electron and ion beams, and electric currents. An unstable wave is characterized by a complex wave frequency, whose real part describes the rate of wave oscillations, and the imaginary part describes the growth rate of instability. The growth rate can be obtained by seeking the complex solution of a plasma dispersion relation. Plasma instabilities can be classified into macroinstabilities and microinstabilities; the former occurs on scales comparable to the bulk scales of the plasma, the latter occurs on scales comparable to the particle motion.

Macroinstabilities are fluid in nature and can be studied by fluid and MHD equations. They are instabilities in the configuration space, thus a macroinstability lowers the energy state of a system by distorting its configuration. Examples of macroinstabilities are Kelvin–Helmholtz instability and Rayleigh–Taylor instability.

The Kelvin–Helmholtz instability is produced by velocity shear flows in fluids and plasmas, such as the transition region between planetary magnetosheath and magnetosphere (Hasegawa et al., 2006). Since the magnetosheath plasma is flowing along the magnetopause around the magnetosphere which has its own flow velocity, the coupling between the magnetosheath and magnetospheric flows causes ripples to grow at the interface by the Kelvin–Helmholtz instability. This velocity shear-driven macroinstability contributes to plasma and momentum transport from the magnetosheath across the magnetopause to the magnetosphere by mixing the two regions.

The Rayleigh–Taylor instability, also known as the interchange instability, is a macroinstability at a fluid or plasma boundary under the influence of a gravitational field. At the boundary, the gravitational field causes ripples to grow at the interface leading to the formation of density bubbles. The growth rate of the Rayleigh–Taylor instability is a function of the gravitational acceleration. This macroinstability occurs frequently at the Earth's equatorial ionosphere, where collisions with neutrals modify considerably the instability leading to the formation of plasma density bubbles known as equatorial spread-F (Woodman, 2009).

Microinstabilities are kinetic in nature and can be studied on the basis of the Boltzmann–Vlasov equations. Microinstabilities are velocity space instabilities related to the distribution function of the plasma particles, and appear when the distribution function of the plasma particles departs from a Maxwellian distribution. There are two types of microinstabilities: electromagnetic and electrostatic instabilities.

An electromagnetic microinstability results from the growth of electromagnetic waves associated with the fluctuation of current densities in the plasma. An example of electromagnetic microinstabilities is the anisotropy-driven instability responsible for the growth of whistler waves in the magnetosphere. Whistler instability may be excited by free energy stored in the temperature anisotropy of hot electrons in the planetary magnetospheric plasma, whose growth rate and instability threshold are functions of the temperature anisotropy. During terrestrial substorms the enhanced temperature anisotropies are induced by plasma convection from the magnetotail into the inner magnetosphere, resulting in the excitation of broadband whistler waves (Horne et al., 2003). These whistler waves can interact strongly with hot electrons of the radiation belts and plasma sheet via electron cyclotron resonance, causing enhanced precipitation of energetic electrons in the auroral regions and in the region of South Atlantic Magnetic Anomaly.

An electrostatic microinstability results from the growth of electrostatic plasma waves associated with the fluctuations of charge densities in the plasma. Examples of electrostatic instabilities are the bump-on-tail instability and the ion-acoustic instability. When an electron beam interacts with a background plasma, a bump-on-tail configuration appears in the distribution function of the plasma electrons. The free energy of the electron beam can produce a beam-plasma instability, leading to the growth of Langmuir waves with frequencies near the background plasma frequency. The growth rate of this instability depends on the electron beam velocity and the instability can be excited if the electron beam velocity exceeds a threshold related to the thermal velocity of the background plasma. Langmuir waves driven by the interaction of the energetic electron beams, emanating from the solar active regions, with the solar atmosphere and solar wind plasmas via the bump-on-tail instability are responsible for the generation of type-III solar radio emissions by solar flares (Lin et al., 1986).

Ion-acoustic waves can be produced by an electrostatic microinstability due to an electron current flowing in a plasma. The combined distribution function consisting of hot drifting electrons and cold immobile ions indicates that an ion-acoustic instability can develop in the region of the electron distribution function where its slope is positive. The growth rate for this current-driven instability depends on the electron drift velocity. It is excited provided the electron drift velocity exceeds the ion acoustic velocity and the electron temperature is much larger than the ion temperature. The unstable ion-acoustic waves excited by the electron current propagate in the direction of the current, at a speed slightly lower than the speed of the current. An ion-acoustic instability can be driven by the field-aligned currents in the Earth's auroral ionosphere, as evidenced by the density irregularities observed along the auroral field lines. Other types of electrostatic and electromagnetic waves can also be induced by currents in space and astrophysical plasmas.

3.3. Nonlinear waves

The planetary–exoplanetary environment is an intrinsically nonlinear system. Although the linear description is sometimes a good approximation, in general it is valid only at the initial stage of a growing instability when the amplitude of unstable waves is still infinitesimally small. When the instability grows, the disturbances reach finite-amplitudes and nonlinear effects begin to affect the system behavior. In the saturated state of instability, the system dynamics is governed by nonlinear effects. In addition to the finite-amplitude effect of disturbances, a variety of other nonlinear effects may appear in fluids and plasmas. These effects may occur on the kinetic level and include the distortion of the undisturbed particle orbits, the interaction between unstably excited particles and waves, and the interactions between waves themselves in which particles are included only to higher order. Schamel and Luque (2005) pointed out that in contrast to the aforementioned standard wave concept, a new paradigm of plasma stability exists whereby nonlinear trapped particle modes such as electron and ion holes can appear in a collisionless plasma due to kinetic processes even though the plasma is linearly stable.

There are many types of nonlinear waves in the planetary–exoplanetary environment at both microscopic and macroscopic scales. Examples of nonlinear waves at the microscopic scales are solitons and double layers. Well-known examples of macroscopic-scale nonlinear waves are the collisionless shock waves. An ion-acoustic soliton results from a balance between wave steepening and wave dispersion. Without wave dispersion, the natural tendency of a wave to steepen, which happens due to the nonlinearity of the medium, will lead to wave breaking. The ion-acoustic soliton has a bell-shaped wave form which propagates at a constant velocity across uniform plasma. It is stable and travels a long distance without changing its shape. There is an inverse relation between the amplitude of a soliton and its width, i.e., the higher the amplitude of a soliton, the narrower its width. Solitons preserve their shapes and velocities after a collision with another soliton. Ion-acoustic solitons can also evolve into double layers due to reflection and transmission of plasma particles in the solitons themselves. In contrast to solitons which do not contain a net potential drop across the soliton, double layers are nonlinear structures containing net potential drops. Hence, a series of double layers if aligned along the magnetic field with correct polarity will add up to produce large electric potential drops along a magnetic field line. Ion-acoustic solitons, ion-acoustic shocks and double layers with large electric fields have been observed by satellites in the regions of auroral plasmas in conjunction with field-aligned currents and ion beams (Marklund, 2009). A balance between wave steepening and dissipation leads to the formation of a shock wave which has a ramp-shape curve. The thickness of the shock ramp is related to dissipation and shock velocity. In the presence of dissipation and dispersion, an ion-acoustic soliton evolves into an oscillatory shock structure (Pottelette et al., 2003). The oscillations occur either upstream or downstream of a shock depending on the external conditions.

A shock is a discontinuity which divides a continuous medium into two different regimes: the regions upstream and downstream of a shock. In a gas-dynamic shock, the physical process is dominated by binary collisions between gas molecules. Particle collisions are rare in regions of the planetary–exoplanetary environment where the plasma density is relatively low, such as solar corona and solar wind. Hence, shocks in space and astrophysical plasmas are collisionless shocks. Examples of collisionless shocks are the Earth's bow shock and interplanetary shocks. A planetary bow shock is produced by the slowing down of the supersonic solar wind by a planetary magnetosphere, forming a standing shock wave in front of the dayside magnetosphere. Interplanetary shocks are the result of mass ejected from solar active regions. These masses travel from the solar atmosphere across the interplanetary medium. Apparently all interplanetary shocks are driven by such CMEs, but only a portion of the CMEs drive an interplanetary shock. Only a small fraction of all CMEs reach 1 AU (Grießmeier et al., 2007a). However, some strong interplanetary shocks can reach the outer boundary of the heliosphere (Webber et al., 2007). Three types of collisionless shocks are found in the solar-terrestrial environment: fast, intermediate, and slow shocks. Planetary bow shocks and most interplanetary shocks are fast MHD shocks. Only a few slow MHD shocks have been identified in solar wind. However, intermediate and slow MHD shocks may be more common in solar corona and have been proposed to exist in relation to magnetic field reconnections.

3.4. Chaos and turbulence

Turbulence is a nonlinear phenomenon where multiscale stochastic and deterministic chaotic processes coexist, characterized by the presence of incoherent as well as coherent spatiotemporal fluctuations. Cosmic plasmas and atmospheric fluids are dynamically evolving turbulent systems whose dynamics is governed by nonlinear wave–wave interactions and nonlinear wave–particle interactions.

Nonlinear wave–wave interactions occur if the waves are resonant or phase-synchronized, described by the phase-matching conditions (i.e., the resonant relations of wave frequencies and wave vectors) which represent physically the conservation of wave energy and momentum. Wave coupling can be treated, approximately, either as coherent interactions (e.g., parametric interactions) where wave phases are fixed, or incoherent interactions (e.g., the random-phase approximation) where wave phases are random. Examples of nonlinear wave–wave interactions are three-wave processes and four-wave processes. For example, two oppositely propagating Langmuir waves can interact to generate a radio wave at the second harmonic plasma frequency, which can explain the origin of nonthermal radio emissions generated by either electron beams accelerated by solar flares or interplanetary shocks in the solar corona and solar wind. Nonlinear wave–wave interactions involving Langmuir waves and ion-acoustic waves have been observed in solar wind in connection with type-III solar radio emissions (Lin et al., 1986; Henri et al., 2009).

Wave–particle interactions occur if waves can exchange energy with particles. In addition to the linear wave–particle interactions such as Landau damping and electron– and ion–cyclotron resonances, various types of nonlinear wave–particle interactions can take place. An important effect of large-amplitude waves is particle trapping, where particles can become trapped in a wave potential trough if the particle kinetic energy in the wave frame is less than the potential energy of the wave. During the evolution of an instability, as the amplitude of wave perturbations increases the particle trapping can readily occur. Both trapped and untrapped plasma particles contribute to the nonlinear evolution of waves and instabilities. Particle trapping removes part of the resonant particles from the particle distribution function which inhibits the ability of these particles to inject energy to the instability, hence leading to the saturation of the instability. For example, the pitch-angle diffusion resulting from the wave–particle interactions involving large-amplitude whistler waves and radiation-belt electrons in the planetary plasmasphere can deplete the resonant electrons and scatter them into the loss cone, leading to enhanced particle precipitation into auroral atmospheres. Bernstein–Greene–Kruskal waves, known as BGK waves, are nonlinear plasma waves resulting from particle trapping and untrapping. For example, the Polar and Cluster satellites in the Earth's magnetosphere, magnetopause and bow shock observed large-amplitude solitary waves called electron holes and ion holes, which are related to BGK waves (Schamel and Luque, 2005; Pickett et al., 2008). Several kinds of nonresonant wave–particle interactions, which do not require any linear resonance, can also occur in plasmas. For example, kinetic Alfvén waves with sufficiently short wavelengths across the background magnetic field may produce superadiabatic acceleration of ions in solar corona (Voitenko and Goossens, 2004). Moreover, stochastic acceleration of charged particles can take place in the presence of nonlinear chaotic waves and turbulence (He, 2003).

A typical power density spectrum of fluid and plasma turbulence shows power-law in frequency and wavenumber, which is an indication of energy cascade and multiscale interactions. Energy transfer in turbulence can occur via either direct cascade or inverse cascade mechanisms. In the direct cascade mechanism, energy is transferred from large scales to small scales, whereas in an indirect cascade mechanism energy is transferred from small scales to large scales. For example, in the nonlinear evolution stage of the collisional Rayleigh–Taylor instability in the Earth's equatorial ionosphere the plasma bubbles can evolve from long wavelengths (of the order of kilometers) to shorter wavelengths (of the order of meters) via the direct cascade mechanism, producing a broadband power spectrum.

In general, turbulence in the planetary–exoplanetary environment is intermittent, exhibiting spatiotemporal variations that switch randomly between bursting periods of large-amplitude fluctuations and quiescent periods of low-amplitude fluctuations. Such intermittent behavior becomes more pronounced at small scales. The statistical approach to turbulence shows that the probability distribution functions of fluctuations are of nearly Gaussian shape at large scales, but become non-Gaussian with sharp peaks and fat tails at small scales. This implies that extreme events, i.e., large-amplitude fluctuations, have a higher probability of occurrence than if they are normally distributed. The coherent (non-Gaussian) structures are localized regions of turbulence where finite phase correlation exists, and they have a typical lifetime longer than the background of stochastic fluctuations.

Turbulence can display chaotic behavior. Chaos in the Earth's atmosphere was discovered by Lorenz (1963) and has contributed significantly to the study of nonlinear wave–wave and wave–particle interactions as well as turbulence in fluids and plasmas. A chaotic system shows sensitive dependence on the system's initial conditions so that nearby orbits will diverge exponentially in time and space. A chaotic system also demonstrates sensitive dependence on small variations of the system parameters. Order and chaos can coexist in a nonlinear dynamical system. The ordered state is described by a stable periodic orbit (regular attractor) and the chaotic state (chaotic attractor) is described by an infinite set of unstable periodic orbits. The dynamical systems approach to turbulence can elucidate the nonlinear dynamics and structures of the planetary–exoplanetary environment, such as Alfvén turbulence (Chian et al., 1998, 2006, 2007; Rempel and Chian, 2005), Langmuir turbulence (De Oliveira et al., 1995; Chian et al., 1996, 2000, 2002; Rizzato et al., 2003) and drift turbulence (He and Chian, 2003; Rempel and Chian, 2007).

In 2D and 3D, turbulence consists of two components: an incoherent component of background flow and a coherent component related to vortices (Farge et al., 2006). The coherent component is a collection of nonlinear multiscale structures, associated with localized regions of concentrated vorticity such as vortices in a turbulent shear flow. Vortices are fairly stable and can persist for a large number of vortex rotation periods. Due to their long lifetimes, vortices play a major role in the transport of mass and momentum in fluids and plasmas.

The study of phase synchronization in a system of coupled oscillators has improved our understanding of a variety of nonlinear phenomena in physical, chemical, and biological systems. Phase synchronization may explain the formation of nonlinear coherent structures such as solitons and vortices in turbulence. The concept of phase synchronization of coupled periodic oscillators has been generalized to coupled chaotic oscillators. For example, the imperfect phase synchronization of the fundamental spectral components with distinct scales in fluids and plasmas can be the origin of the intermittent bursts of wave energy in turbulence (He and Chian, 2003). There is finite phase coherence in wave interactions in turbulence, as evidenced in the magnetic field turbulence observed upstream of the Earth's bow shock and in the ambient solar wind (Koga et al., 2007; Chian and Miranda, 2009) and in the fluid turbulence observed in the Earth's atmosphere (Chian et al., 2008).

4. Cyclotron masers in the planetary–exoplanetary environment

As mentioned in Section 1, Earth, Jupiter, Saturn, Uranus and Neptune are known to radiate intense radio waves (Chian, 1993; Zarka, 1998, 2004; Treumann, 2006). These radio emissions are nonthermal since they are emitted by nonthermal particles (e.g., cyclotron maser instability) and their brightness temperature is greater than the background plasma temperature. A variety of nonthermal planetary radio emissions are observed, e.g., Auroral Kilometric Radiation (AKR), Jovian Decametric Radiation, nonthermal continuum radiation, and radio emissions upstream of planetary bow shocks. The generation mechanisms of nonthermal planetary radio waves can be classified as: linear direct (e.g., cyclotron maser), linear indirect (e.g., mode conversion), nonlinear direct (e.g., double layer and stimulated scattering), nonlinear indirect (e.g., wave–wave interactions and soliton). Most nonthermal planetary radio emissions in the solar system are influenced by magnetospheric substorms (Wu and Lee, 1979) driven by solar activities such as flares, coronal mass ejections or corotating interaction regions, thus providing the electromagnetic signature of solar-planetary coupling. In this section, we discuss the generation of nonthermal radio emissions by cyclotron masers, and in the next section we discuss chaos in nonthermal radio emissions.

Twiss (1958) showed that an electron cyclotron maser can amplify electromagnetic radiation in a plasma near the electron cyclotron frequency and its harmonics when relativistic electrons interact resonantly with electromagnetic waves at the Doppler shifted electron–cyclotron frequency

$$\omega - k_{\parallel} v_{\parallel} = \frac{n\omega_{ce}}{\gamma}, \tag{1}$$

where ω is the wave frequency, $\mathbf{k} = (k_{\parallel}, k_{\perp})$ is the wave vector, $\mathbf{v} = (v_{\parallel}, v_{\perp})$ is the resonant electron velocity, the subscripts $\parallel$ ($\perp$) denote parallel (perpendicular) to the ambient magnetic field B_0, $\gamma = (1 - v^2/c^2)^{-1/2}$, $\omega_{ce} = eB_0/m_e$ is the electron cyclotron frequency, and n denotes the cyclotron harmonic number. Relativistic phase bunching in the cyclotron motion of electrons, with transverse energy above a few keV, can lead to coherent radiation analogous to quantum masers.

Chu and Hirshfield (1978) derived a linear relativistic dispersion relation for fast and slow circularly polarized electromagnetic waves propagating along an ambient magnetic field

$$\omega^2 - k_{\parallel}^2 c^2 = \frac{\omega_{pe}^2}{\gamma_0}\left[\frac{\omega}{\omega - \omega_{ce}/\gamma_0} + \frac{k_{\perp}^2 v_{\perp 0}^2 \left(1 - \omega^2/k_{\parallel}^2 c^2\right)}{2(\omega - \omega_{ce}/\gamma_0)^2}\right], \tag{2}$$

where the electron plasma frequency $\omega_{pe} = N_0 e^2/m_e$ and $\gamma_0 = \left(1 - v_{\perp 0}^2/c^2\right)^{-1/2}$. By assuming real k and complex ω, Eq. (2) shows the existence of unstable solutions of the fast and slow electromagnetic waves that correspond to the amplification of radiation due to the relativistic phase bunching of electrons.

Wave growth is possible if the electron distribution function $f(v_{\parallel}, v_{\perp})$ contains free energy. The growth rate of an electron cyclotron maser instability can be written as (Zarka, 2004)

$$\gamma = \mathrm{Im}(\omega) \propto \int\int v_{\perp}^2 (\partial f/\partial v_{\perp}) \delta(\omega - k_{\parallel} v_{\parallel} - \omega_{ce}/\gamma)\, dv_{\parallel}\, dv_{\perp}. \tag{3}$$

It shows that the condition for wave amplification is an anisotropic electron distribution such that $\partial f/\partial v_{\perp} > 0$, which constitutes a population inversion.

Cyclotron maser is widely accepted as the source of Auroral Kilometric Radiation. AKR is produced near the electron cyclotron frequency on auroral field lines in the upward current auroral regions of depleted density ($\omega_{pe} < \omega_{ce}$) where downgoing electrons are accelerated (Gurnett, 1974; Ergun et al., 2000). The AKR radio waves propagate primarily in the R-X (right-hand extraordinary) mode and show strong temporal variations and fine spectral features. Initially, the free energy of AKR cyclotron maser was postulated to be electrons with loss-cone distribution (Wu and Lee, 1979; Melrose and Dulk, 1982). Later, some studies based on computer simulations (Pritchett, 1984a; Pritchett and Strangeway, 1985) and Viking observations (Louarn et al., 1990) demonstrated that the loss-cone distribution is insufficient to power AKR. Pritchett (1984b) and Winglee and Pritchett (1986) showed that a shell (or horseshoe) distribution of electrons produced by parallel electric field can excite cyclotron maser emissions more efficiently than a loss-cone distribution. This has been confirmed by computer simulations (Pritchett et al., 1999) and FAST satellite observations (Ergun et al., 2000). Another electron distribution function with a ring-type distribution in perpendicular (with respect to the ambient magnetic field) velocity space can also generate cyclotron maser at quasi-perpendicular shocks (Bingham et al., 2003; Yoon et al., 2007) or plasma turbulence regions where plasma waves propagate mainly perpendicular to the ambient magnetic field.

5. Chaos in the planetary–exoplanetary environment

There is a wealth of observational and theoretical evidence of chaos and intermittent turbulence in the solar-terrestrial environment including solar dynamo, solar atmosphere, solar wind, and terrestrial magnetosphere–ionosphere–atmosphere (Chian et al., 2006). Hence, the study of chaos and intermittent turbulence driven by chaos is essential for understanding the complex nature of the planetary–exoplanetary environment. In this section, we give an example of chaos arising from nonlinear wave–wave interactions in connection with nonthermal radio emissions.

Plasma radio emissions generated by Langmuir-ion acoustic turbulence through nonlinear three-wave interactions (Melrose, 1991; Chian and Abalde, 1995; Rizzato et al., 2003) have been observed in planetary foreshocks (Kuncic and Cairns, 2005), type-III solar radio bursts (Lin et al., 1986; Henri et al., 2009) and type-II radio bursts from interplanetary shocks (Ledenev et al., 2008). A schematic diagram depicting the emission of nonthermal radio emissions by nonlinear wave–wave interactions in plasmas, via either a Langmuir–Alfvén turbulence or a Langmuir-ion acoustic turbulence, is shown in Fig. 1. A model of nonthermal radio emission near the electron plasma frequency in planetary magnetospheres was proposed by Chian et al. (1994) whereby a large-amplitude Langmuir wave (L) (evolved from a bump-on-tail instability) interacts with an Alfvén wave (A) to generate an electromagnetic whistler wave (W) through a parametric instability, when the pump amplitude exceeds a threshold condition. This three-wave interaction is represented as $L \rightleftharpoons W \pm A$, which may explain the excitation of whistler-mode radio emissions in the Earth's and Jupiter's auroral acceleration regions, where the electron plasma frequency is smaller than the electron cyclotron frequency. It provides an emission mechanism for the leaked AKR detected on the ground. Note that the leaked AKR (Oya et al., 1985)

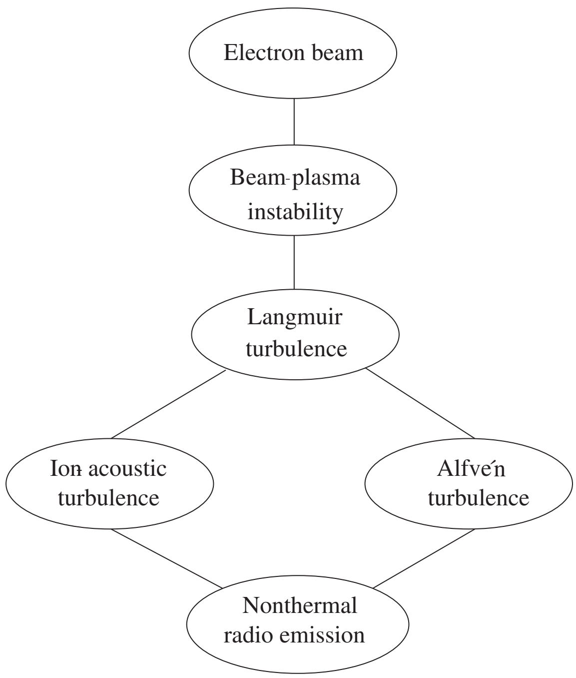

Fig. 1. Schematic diagram of nonthermal radio emission generated by nonlinear wave–wave interactions induced by electron beam.

detectable by the ground receivers is generated by a different physical mechanism from the traditional AKR discussed in Section 4 which is reflected off the ionosphere and cannot reach the ground. Observational evidence in the Earth's magnetosphere in support of this nonthermal planetary radio emission process has been found (Chian et al., 1994). Alternatively, Fig. 1 shows that nonthermal radio emissions can be produced via a Langmuir-ion acoustic turbulence. This three-wave interaction involves an electron-beam driven Langmuir wave (L), a transverse electromagnetic wave (T) and an ion-acoustic wave (S), which is represented as $L \rightleftharpoons T \pm S$ (Melrose, 1991; Chian and Abalde, 1995; Rizzato et al., 2003). It provides an emission mechanism for nonthermal radio emissions in planetary foreshocks and interplanetary medium (Lin et al., 1986; Kuncic and Cairns, 2005; Henri et al., 2009).

A nonlinear theory of the nonthermal radio emission model of Chian et al. (1994) was formulated by Lopes and Chian (1996), taking into account the effects of pump depletion, wave dissipation and frequency mismatch. This nonlinear theory can explain the fine structures of auroral whistler-mode radio emissions and the amplitude modulation of auroral Langmuir waves; however, chaos does not appear because no energy source is included. Chian et al. (2000, 2002) and Rempel et al. (2003) developed a chaos theory of the nonlinear three-wave model of auroral radio emissions, by considering energy injection through a linearly unstable Langmuir wave driven by an electron beam. The set of equations governing the nonlinear dynamical evolution of $L \rightleftharpoons W + A$ that satisfies the phase-matching conditions

$$\mathbf{k}_\mathrm{L} = \mathbf{k}_\mathrm{W} + \mathbf{k}_\mathrm{A}, \tag{4}$$

$$\omega_\mathrm{L} \approx \omega_\mathrm{W} + \omega_\mathrm{A}, \tag{5}$$

is given by

$$\dot{A}_\mathrm{L} = \nu_\mathrm{L} A_\mathrm{L} + A_\mathrm{W} A_\mathrm{A}, \tag{6}$$

$$\dot{A}_\mathrm{W} = \nu_\mathrm{W} A_\mathrm{W} - A_\mathrm{L} A_\mathrm{A}^*, \tag{7}$$

$$\dot{A}_\mathrm{A} = i\delta A_\mathrm{A} + \nu_\mathrm{A} A_\mathrm{A} - A_\mathrm{L} A_\mathrm{W}^*, \tag{8}$$

where A_L, A_W and A_A represent the normalized complex amplitude (see, e.g., Chian et al., 2000) of the Langmuir, whistler and Alfvén wave, respectively, δ represents the normalized frequency mismatch; ν_L, ν_W and ν_A represent the wave growth/damping rates for the Langmuir, whistler and Alfvén waves, respectively. The Langmuir wave is assumed linearly unstable by setting $\nu_\mathrm{L} = 1$, whereas the whistler wave and Alfvén wave are assumed linearly damped by setting $\nu_\mathrm{W} = \nu_\mathrm{A} \equiv \nu < 0$.

Chaos can appear in the nonlinear evolution of three-wave interactions, depending on the value of the system parameter ν. Fig. 2a shows the bifurcation diagram of Eqs. (6)–(8). This diagram was constructed by numerically

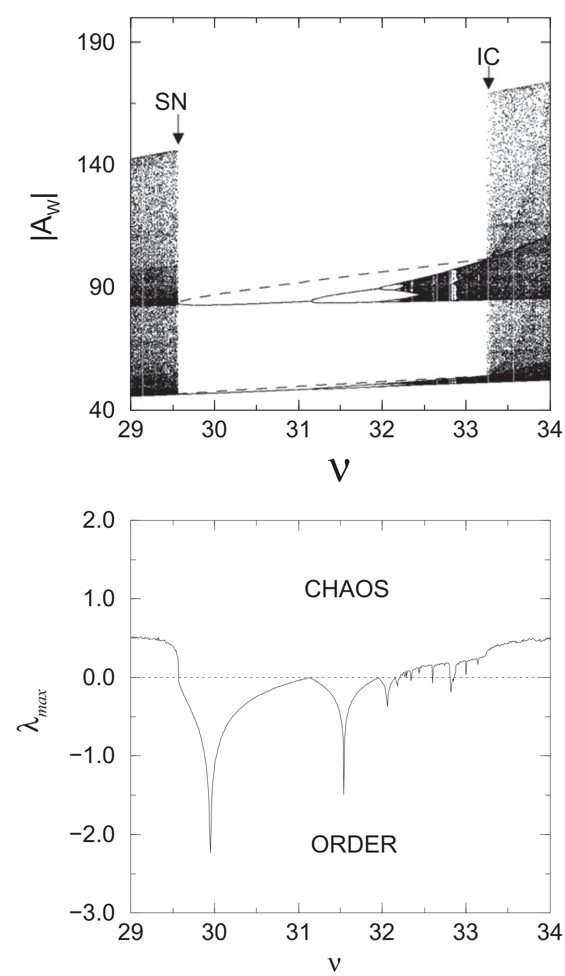

Fig. 2. Upper panel: Bifurcation diagram for $|A_\mathrm{W}|$ as a function of ν in a period-2 window. Lower panel: Maximum Lyapunov exponent λ_MAX as a function of ν. The dashed lines denote the period-2 unstable periodic orbit; SN denotes saddle-node bifurcation; IC denotes interior crisis.

integrating Eqs. (6)–(8) for each value of parameter ν, dropping the initial transient. As ν is increased, there is a sudden transition from chaos to order via a saddle-node bifurcation, marked as SN in Fig. 2a, where a pair of period-2 stable and unstable periodic orbits is created at $\nu_{SN} = 29.56$. The stable periodic orbit undergoes a cascade of period-doubling bifurcations, leading to chaos. At $\nu = \nu_{IC} = 33.23$, the chaotic attractor collides with a period-2 unstable periodic orbit evolving from the saddle-node bifurcation, leading to an interior crisis (IC). The degree of chaoticity of this three-wave process is characterized by calculating the maximum Lyapunov exponent λ_{MAX}, shown in Fig. 2b. Chaos (aperiodic solutions) occurs when $\lambda_{MAX} > 0$, and order (periodic solutions) occurs when $\lambda_{MAX} < 0$.

Two types of intermittency, due to either local or global bifurcations, can be observed in the chaotic time series around the transition regions. In the type-I Pomeau–Manneville intermittency, laminar phases of nearly periodic oscillations are suddenly interrupted by chaotic bursts. This intermittency occurs in the transition region of a saddle-node bifurcation when $\nu < \nu_{SN}$. An example of time series for this intermittency is given in Fig. 3. Fig. 3a shows a periodic solution with period-two when $\nu_{SN} = 29.56$; Fig. 3b shows an intermittent solution just to the left of ν_{SN}; and Fig. 3c shows a stronger chaotic solution further away from ν_{SN}. The crisis-induced intermittency is characterized by a time series containing laminar phases of weakly chaotic fluctuations which are randomly interrupted by strongly chaotic bursts. Some

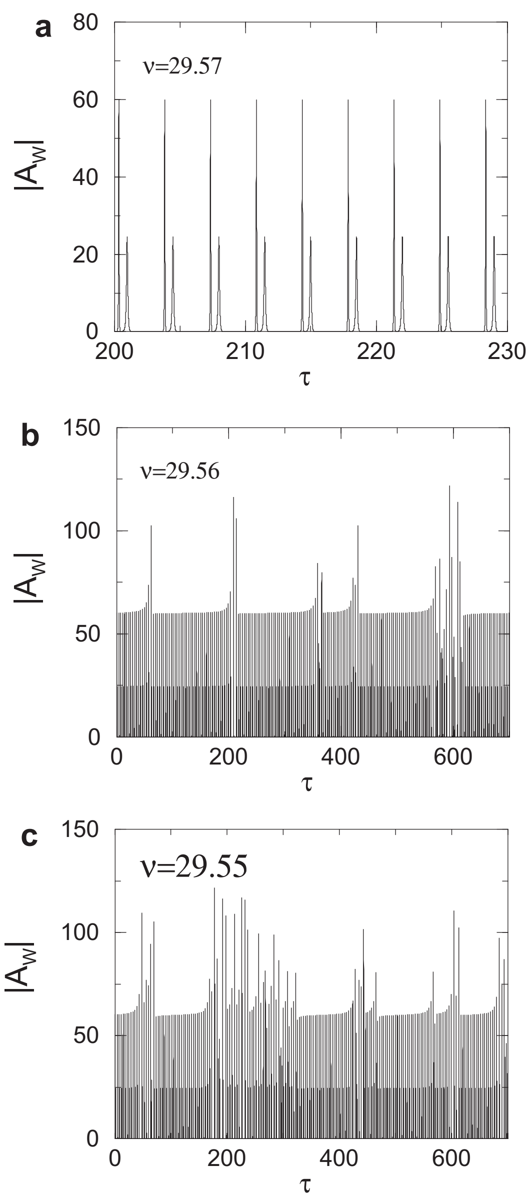

Fig. 3. Time series of $|A_W|$ as a function of τ for the type-I Pomeau–Manneville intermittency route to chaos for: (a) $\nu = 29.57$, (b) $\nu = 29.56$, and (c) $\nu = 29.55$.

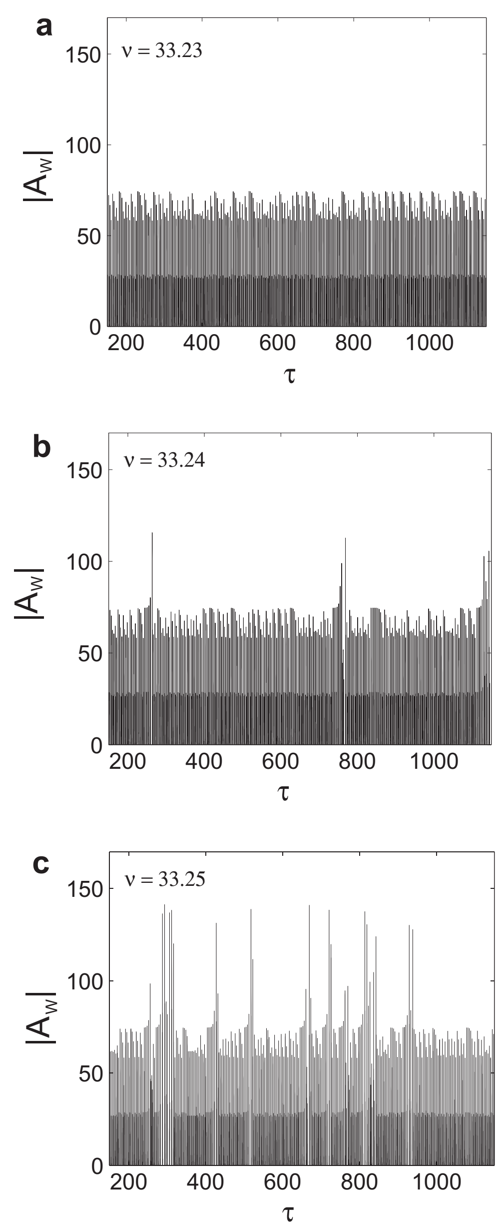

Fig. 4. Time series of $|A_W|$ as a function of τ for the crisis-induced intermittency for: (a) $\nu = 33.23$, (b) $\nu = 33.24$, and (c) $\nu = 33.25$.

examples of the time series for this crisis-induced intermittency are shown in Fig. 4.

The above model of chaos can be applied to all nonlinear three-wave interactions in plasmas and fluids, including the plasma emission process $L \rightleftharpoons T \pm S$ indicated in Fig. 1 (by simply replacing W by T and A by S). The three-wave model of auroral radio emissions of Chian et al. (1994) has been extended to study the nonlinear excitation of kinetic Alfvén waves and whistler waves by electron-beam driven Langmuir waves in solar corona (Voitenko et al., 2003). Kinetic Alfvén waves have been observed by satellites in the Earth's magnetosphere and AKR source region, and play an important role in energy release and transport in the planetary–exoplanetary environment. Another nonlinear process (Sirenko et al., 2002) involving three-wave parametric interaction of kinetic Alfvén waves with ordinary-mode and extraordinary-mode radio waves was investigated for solar corona.

6. Conclusion

In this paper, we presented a brief overview of some basic linear and nonlinear plasma processes in the planetary–exoplanetary environment. We showed that the magnetic field plays a key role in the planetary–exoplanetary environment, e.g., in the generation of nonthermal planetary radio emissions by cyclotron masers and by nonlinear wave–wave interactions involving Langmuir waves and Alfvén waves. The magnetic field also plays an important role in other astrophysical phenomena such as the formation and evolution of planets and stars, accretion disks, stellar and extragalactic jets and outflows, interstellar and intergalactic media, galactic center, and the primordial universe. Hence, the study of nonlinear and chaotic processes in the planetary–exoplanetary environment has relevant applications to plasma astrophysics. In particular, the investigation of magnetic field reconnection, collisionless shocks, particle acceleration, and nonthermal radio emissions in the planetary–exoplanetary environment can improve our understanding of similar processes in astrophysical plasmas.

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