ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

Periodic Change of Solar Differential Rotation

S.-I. Itoh, K. Itoh, A. Yoshizawa and N. Yokoi

(Received - Apr. 21, 2004)

NIFS-800 May 2004

TOKI, JAPAN

Periodic change of solar differential rotation

S. -I. Itoh
Research Institute for Applied Mechanics, Kyushu University 87, Kasuga 816-8580, Japan
s-iitoh@riam.kyushu-u.ac.jp

K. Itoh
National Institute for Fusion Science, Toki 509-5292, Japan
itoh@nifs.ac.jp

A. Yoshizawa[1]
3-2-10-306, Tutihasi, Miyamae-ku, Kawasaki 216-0005, Japan
ay-tsch@mbg.nifty.com
and

N. Yokoi
Institute of Industrial Science, University of Tokyo, Komaba, Tokyo 153-8505, Japan
nobyokoi@iis.u-tokyo.ac.jp

ABSTRACT

The periodic oscillation of the inhomogeneous rotation of the sun is studied by use of the MHD dynamo theory. There exists a turbulent electromotive force which is driven by the vorticity of the flow (i.e., the γ dynamo). In addition, its counterpart exists in the vorticity equation, that is, the rotation is induced by inhomogeneous magnetic field in turbulent plasma. Based on this dynamo theory, a periodic change of solar differential rotation with the period of 11 yr is theoretically explained. The predicted amplitude is compared with observations.

Keywords: helioseismology, solar rotation, solar magnetic field, differential rotation, cross-helicity dynamo, zonal flow, turbulence

1. Introduction

Recent progress of the solar observation based on helioseismology (Gough et al. 1996; Thompson et al. 1996; Shibahashi 2002; Lang 2001) has shown that the azimuthal rotation velocity is inhomogeneous in the convection zone as well as on the surface of the sun. The rotation velocity changes in the radial and polar directions. This inhomogeneity of solar rotation velocity is accompanied by a steep gradient, the solar tachocline. (See Lang 2001; Spiegel & Zahn 1992; Gilman 2000; Tobias 2003, for its comprehensive review.) In addition, the inhomogeneity of rotation (zonal flow) changes in time. It has been known that the rotational speed of the solar surface has periodic change with the 11-yr period. (See Ulrich 2001, and references therein.) This 11-yr oscillation of azimuthal rotation velocity has been identified even in the convection zone (Howe et al. 2000a; Vorontsov et al. 2002). This periodic oscillation shows a similarity with the pattern of the solar magnetic activity. The phenomenological observation suggested

[1] Visiting Professor, National Institute for Fusion Science, Toki 509-5292, Japan

a causal relation between the periodic change of differential rotation and solar dynamo cycle. Nevertheless, origin of periodic oscillation of rotation velocity remains unexplained.

The spontaneous generation of the radial and poloidal inhomogeneity of the solar rotation velocity has a similarity to the so-called transport barrier phenomena of toroidal plasmas in laboratory experiments. The internal transport barrier in toroidal plasma is such a phenomenon that the turbulent transport coefficient changes abruptly across a certain magnetic surface (i.e., the barrier as a spatial phase boundary). (See, e.g., Itoh, Itoh, & Fukuyama 1999; Yoshizawa, Itoh, & Itoh 2003, for a review.) In the vicinity of the barrier, the plasma rotation velocity, which is averaged over a magnetic surface, has a steep radial gradient. The solar rotation inhomogeneity and the transport barrier in toroidal plasmas form at least a pair of central issues in the structure formation of nonequilibrium turbulent plasmas.

The inhomogeneity of solar rotation has been studied in conjunction with the solar dynamo problem (Gilman 2000; Tobias 2003; Parker 1993; Yoshizawa et al. 2004). In the theory of dynamo, it has been pointed out that the flow vorticity induces the electromotive force, being named γ dynamo, and that its counterpart exists in the vorticity equation (Yoshizawa et al. 2004; Yoshizawa 1990; Yoshizawa et al. 1998). The inhomogeneity of the magnetic field can drive the flow. That is, the driven flow tends to be aligned with respect to the magnetic field. Based upon this γ-dynamo theory, a mechanism of the internal transport barrier formation in toroidal plasma has been discussed (Yoshizawa et al. 1998). In this article, the influence of turbulent flow generation due to the magnetic field in the solar convection zone is studied. The inhomogeneous azimuthal rotation velocity is shown to be induced by the dynamo magnetic field in the sun. A theoretical model is presented for the periodic oscillations of the differential rotations (torsional oscillations) in the convection zone and on the surface of the sun. This periodic change is induced by the solar magnetic activity cycle which has the period of 22 yr. The model explains the 11-yr oscillation of differential rotation in the solar convection zone and on the surface.

2. Mean-Field Equations

The dynamo theory of turbulent plasma has shown (Gilman 2000; Ulrich 2001) that the flow is governed by

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} u_i u_j = -\frac{\partial p}{\partial x_i} + 2\,(\boldsymbol{u}\times\boldsymbol{\omega}_{\rm F})_i + (\boldsymbol{J}\times\boldsymbol{B})_i + \frac{\partial}{\partial x_j}(-R_{ij}) + \nu\nabla^2 u_i, \quad (1)$$

in the frame rotating with angular velocity $\boldsymbol{\omega}_{\rm F}$, while the corresponding magnetic field is described by

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{u}\times\boldsymbol{B} + \boldsymbol{E}_{\rm T}) + \eta\nabla^2\boldsymbol{B}. \quad (2)$$

Here $\mathbf{u}$ is the relative velocity in the rotation frame, p is the pressure per unit mass with effects of microscopic pressure fluctuation included, $\boldsymbol{B}$ is the magnetic field, $\boldsymbol{J}(=\nabla\times\boldsymbol{B})$ is the electric current, ν is the kinematic viscosity, and η is the magnetic diffusivity. These equations are given in the Alfvén unit, where the magnetic field is normalized by $\sqrt{\mu_0\rho}$ and is measured in m s^{-1} (ρ is the mass density).

The Reynolds stress R_{ij} and the turbulent electromotive force $\boldsymbol{E}_{\rm T}$, which express effects of microscopic velocity and magnetic field, are given by

$$\begin{aligned} R_{ij} &\equiv \langle u'_i u'_j - B'_i B'_j \rangle \\ &= -\frac{1}{3}\langle \boldsymbol{u}'^2 - \boldsymbol{B}'^2 \rangle \delta_{ij} \\ &+ \nu_{\rm T}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) - \nu_{\rm M}\left(\frac{\partial B_j}{\partial x_i} + \frac{\partial B_i}{\partial x_j}\right), \end{aligned} \quad (3)$$

$$\boldsymbol{E}_{\rm T} \equiv \langle \boldsymbol{u}'\times\boldsymbol{B}' \rangle = \alpha\boldsymbol{B} - \beta\boldsymbol{J} + \gamma\,(\boldsymbol{\omega} + 2\boldsymbol{\omega}_{\rm F}), \quad (4)$$

where $\boldsymbol{\omega} = \nabla\times\boldsymbol{u}$, primed quantities express microscopic (fluctuating) parts of velocity and magnetic field, and $\langle\cdot\rangle$ denotes the averaging over a global scale. The coefficients α etc. are closely linked with the statistical properties of microscopic velocity and magnetic field, and are written as

$$\alpha = C_\alpha \tau_{\rm m} H,\ \ \beta = C_\beta \tau_{\rm m} K,\ \ \gamma = C_\gamma \tau_{\rm m} W, \quad (5a)$$

$$\nu_{\rm T} = \frac{7}{5}\beta,\ \ \nu_{\rm M} = \frac{7}{5}\gamma. \quad (5b)$$

Here the turbulent residual helicity H, the turbulent energy K, and the turbulent cross helicity W are defined by

$$H = \langle -\boldsymbol{u}'\cdot\boldsymbol{\omega}' + \boldsymbol{B}'\cdot\boldsymbol{J}' \rangle, \quad (6)$$

$$K = \left\langle \frac{u'^2 + B'^2}{2} \right\rangle , \quad (7)$$

$$W = \langle u' \cdot B' \rangle , \quad (8)$$

respectively. Moreover C_α, C_β, and C_γ are numerical factors, and τ_m is a characteristic time scale of microscopic velocity and magnetic field.

We substitute equation (4) into equation (2), and neglect the molecular magnetic diffusivity as compared with the turbulence counterpart β. Then we have

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times [\boldsymbol{u} \times \boldsymbol{B} + \alpha \boldsymbol{B} - \beta \boldsymbol{J} + \gamma (\boldsymbol{\omega} + 2\boldsymbol{\omega}_F)] . \quad (9)$$

Under the approximation of dropping $\boldsymbol{u} \times \boldsymbol{B}$, the quasi-stationary state of $\boldsymbol{B}$ may occur through the condition

$$\boldsymbol{J} = \frac{1}{\beta} [\alpha \boldsymbol{B} + \gamma (\boldsymbol{\omega} + 2\boldsymbol{\omega}_F)] . \quad (10)$$

This approximation will be later shown to be plausible.

We substitute equation (10) into equation (1) and neglect the spatial variation of α etc. We take the curl of the resulting equation, and have

$$\frac{\partial \boldsymbol{\omega}}{\partial t} = \nabla \times \left[2 \left(\boldsymbol{u} - \frac{\gamma}{\beta} \boldsymbol{B} \right) \times \boldsymbol{\omega}_F + \nu_T \nabla^2 \left(\boldsymbol{u} - \frac{\gamma}{\beta} \boldsymbol{B} \right) \right] . \quad (11)$$

The source of the torque $\nu_T \nabla^2 (\gamma \boldsymbol{B}/\beta)$ in equation (11) is the counterpart of the γ-related term in the right-hand side (RHS) of equation (9).

3. Investigation into Rotation Velocity

Equation (11) describes an interesting effect of the magnetic field on the *generation* of global vorticity. The terms which have the coefficient ν_T in the RHS of equation (11) are induced by the microscopic turbulence. The term $\nabla \times \nu_T \nabla^2 \boldsymbol{u}$ is the well-known turbulent viscosity term, i.e., the localized vorticity decays in time. It tends to eliminate the inhomogeneity of the vorticity. (For instance, the tachocline is weakened by this term.) On the contrary, the term $\nabla \times \nu_T \nabla^2 (\gamma \boldsymbol{B}/\beta)$ generates the vorticity so that the velocity $\boldsymbol{u}$ becomes parallel to $\boldsymbol{B}$. If the localized magnetic field exists, then this dynamo term *generates* the localized flow profile.

A stationary state of equation (11) may occur for

$$\boldsymbol{u} = \frac{\gamma}{\beta} \boldsymbol{B} . \quad (12)$$

From equation (12), we study that the response of the toroidal velocity appears against the change of the magnetic field $\boldsymbol{B}$. When the change is slow in comparison with the diffusion time,

$$|\partial \boldsymbol{\omega} / \partial t| \ll \left| \nu_T \nabla^2 \boldsymbol{\omega} \right| , \quad (13)$$

the response of the relative velocity $\boldsymbol{u}$ in the presence of the temporal variation of $\boldsymbol{B}$, $\delta \boldsymbol{u}$, is given from equation (12) as

$$\delta \boldsymbol{u} = \frac{\gamma}{\beta} \boldsymbol{B} . \quad (14)$$

When we apply this result (14) to the case of sun, the modulation of the toroidal velocity by the dynamo magnetic field is deduced. Here we use polar coordinates (r, ζ, θ), where r is radius, ζ is the azimuthal angle (longitude), and θ is the polar angle (latitude). The dynamo magnetic field is known to have a strong toroidal magnetic field. This magnetic field is localized in the mid- and low-latitude regions. Equation (14) shows that the azimuthal velocity in the rotation frame is stronger in the mid- and low-latitude regions. This localized azimuthal flow has an up-down symmetry. The polarity rule of solar dynamo is well known: the sign of dynamo magnetic field is opposite between northern and southern hemispheres. It should be also noticed that the dynamo coefficient γ is a pseudoscalar while β is a scalar. That is, the ratio γ/β changes the sign in the northern and southern hemispheres. From these facts, the induced modification of the velocity $\delta \boldsymbol{u}$ has an up-down symmetry. This symmetry property of the induced velocity $\delta \boldsymbol{u}$, together with the localization in the latitude, is common to the profile of the solar rotation velocity.

We next estimate the magnitude of the induced velocity $\delta \boldsymbol{u}$. The strength of the magnetic field is evaluated as about 1 T or less in the convection zone of the sun. The location $r/R_\odot \sim 0.8 - 0.9$ may be relevant as the representative value in the study of the inhomogeneous rotation velocity. As the mass density in this region (Yoshizawa et al. 2004; Yoshizawa, Kato, & Yokoi 2000; Priest 1982), we adopt the number density of hydrogen as $O(10^{28})$ m^{-3} or $\rho \sim 10$ kg m^{-3}, which gives that

$$|\boldsymbol{B}| \sim 300 \text{ m s}^{-1} \qquad (15)$$

for $|\boldsymbol{B}| = 1$ T in the Alfvén unit. The turbulence theory has given the bounds of the ratio γ/β as

$$\left|\frac{\gamma}{\beta}\right| \cong \frac{|W|}{K} \leq 1. \qquad (16)$$

(See eq. [5a]).

Combining the estimate (15) with the relation (16), we calculate the induced change of azimuthal velocity. An estimate of the ratio of $|\gamma/\beta| = O(10^{-2}) - O(10^{-1})$ has been given for the study of the γ-dynamo mechanism for the generation of solar magnetic field (Yoshizawa, Kato, & Yokoi 2000). If one employs the mean value of the range in this estimate, $|\gamma/\beta| = 3 \times 10^{-2}$, we have an evaluation of $\delta \boldsymbol{u}$ as

$$|\delta \boldsymbol{u}| \sim 10 \text{ m s}^{-1}. \qquad (17)$$

This is a few percent of the differential rotation velocity in the solar convection zone.

From this estimate, several conclusions are made. First, the turbulent torque generates a localized azimuthal flow through the generation of global magnetic field. The pattern of the periodic change of differential rotation follows the pattern of the solar magnetic cycle. The magnitude of this induced velocity is given by equation (17). Second, this flow is predicted to oscillate in time. The solar magnetic field shows a quasi-periodic change with the period of about 22 yr. As a result of this periodic change of $\boldsymbol{B}$, the induced velocity $\delta \boldsymbol{u}$ is also subject to the (quasi-)periodic change. Two cases can be considered depending on the changeability of the sign of γ/β. If the sign of γ/β is not altered by the change of the polarity of the magnetic field, then $\delta \boldsymbol{u}$ changes its direction and magnitude with the period of 22 yr. In the opposite case, i.e., γ/β changes the sign together with $\boldsymbol{B}$, then $\delta \boldsymbol{u}$ changes its magnitude with the period of 11 yr. It is therefore plausible that the periodic oscillation of differential rotation is composed of the component with the 11-yr period and the one with 22-yr period. Third, the perturbed velocity $\delta \boldsymbol{u}$ is larger near the surface and smaller near the bottom of the convection zone. The radial profile of $\delta \boldsymbol{u}$ is determined by the profiles of the mass density, magnetic field, and the dynamo coefficient γ/β. All of these three change radially, but the density variation may be stronger than other two. This suggests that $\delta \boldsymbol{u}$ is larger near the surface. Fourth, more rapid changes of the rotation are possible to occur. The generated flow $\delta \boldsymbol{u}$ changes following the toroidal component of the dynamo magnetic field. Each magnetic flux tube of the solar dynamo magnetic field is considered to move in the convection zone of the sun. Associated with this motion of the flux tube, the toroidal velocity changes as well.

These theoretical predictions are compared with observational results. First of all, the resemblance of the spatio-temporal patterns of the periodic change of rotation and of the magnetic activity is understood naturally. Second, the amplitude of the periodic oscillation is in a range of observation: the amplitude of oscillation of $1 - 5$ Hz has been observed in the upper convection zone. The radial profile of the amplitude of oscillation is reported in Vorontsov et al. (2002), and $\delta \boldsymbol{u}$ is shown to have larger amplitude near the surface. The main elements of the observation on the periodic change can be explained by the γ-dynamo theory.

The difference of rotation rates at two radii across the region of the steepest gradient of tachocline has been reported to change in time: an year-range evolution is reported in, e.g., Lang (2001); Vorontsov et al. (2002); Howe et al. (2000b). This annual oscillation of velocity difference may be attributed to the motion of toroidal magnetic flux tube.

4. Concluding Remarks

In this work, we studied the influence of the turbulent torque which is coupled with the magnetic field. This torque has been predicted as a counterpart of the γ dynamo, i.e., the turbulent electromotive force associated with the vorticity. This process is applied to the solar dynamo, and the strong azimuthal magnetic field in the sun is predicted to induce the azimuthal velocity which is localized in the mid- and low-latitude regions. This velocity has oscillation period of either 22 yr or 11 yr, depending on the change of the γ-dynamo coefficient, γ/β. The amplitude of oscillation is predicted as equation (17). The spatial pattern, period, and the amplitude of the periodic change of solar rotation in convection zone can be explained by this theoretical model. Further study of the correlation between the flow and the magnetic field will provide a test for this model.

Relation (14) holds when equation (13) is satisfied. Observational data (Ulrich 2001) seems to support this assumption, i.e., the phase difference between the patterns of velocity change and magnetic activity is not large. The phase difference between $\delta \boldsymbol{u}$ and $\boldsymbol{B}$ is another important issue that gives an information about the turbulent viscosity. Whether equation (13) holds for the temporal oscillation with the period of 11 yr (or 22 yr) or not depends on how large the turbulent viscosity $\nu_{\rm T}$ is. An estimate of $\nu_{\rm T}$ has been discussed, showing that $\nu_{\rm T} L^{-2}$ is several times 10^{-8} $\rm s^{-1}$ where L is the thickness of the convection zone (Yoshizawa, Kato, & Yokoi 2000). The frequency of 11-yr (or 22-yr) oscillation of solar magnetic field, $\omega_{\rm smf} \sim O(10^{-8})$ $\rm s^{-1}$, is smaller than this evaluation of $\nu_{\rm T} L^{-2}$. The approximation of equation (14) is not bad, but this oscillation rate $\omega_{\rm sd}$ gives rise to the phase delay of the induced flow $\delta \boldsymbol{u}$ against the source magnetic field $\boldsymbol{B}$ as

$$\phi_{\rm delay} = \arctan\left(\omega_{\rm smf} \nu_{\rm T}^{-1} L^2\right) . \qquad (18)$$

By measuring the phase delay of the 11-yr and 22-yr variation of the inhomogeneous rotation of solar convection zone against the solar magnetic activity, one can obtain an estimate of the turbulent viscosity.

One might wonder whether this induced velocity itself is an origin of the solar differential rotation and tachocline. At this moment, it is not yet conclusive. In order to conclude about this process, the back interaction of $\delta \boldsymbol{u}$ on the solar magnetic field must be taken into account for the determination of the dynamo magnetic field. (See, e.g., Dikpati et al. 2004) The magnetic field and inhomogeneous rotation must be solved simultaneously. We leave this problem for the future analysis

Authors acknowledge the discussion with Prof. H. Shibahashi and Prof. P. H. Diamond. This work is partly supported by the Grant-in-Aid for Scientific Research of Ministry of Education, Culture, Sports, Science and Technology, Japan, by the collaboration program of National Institute for Fusion Science and by the collaboration program of the Research Institute for Applied Mechanics of Kyushu University. Part of this work was performed when one of the authors (AY) was a visiting professor at National Institute for Fusion Science.

REFERENCES

Dikpati, M., de Toma, G., Gilman, P. A., Arge, C. N., & White, O. R. 2004, ApJ, 601, 1136

Gilman, P. A. 2000, Sol. Phys., 192, 27

Gough, D. O., et al. 1996, Science, 272, 1296

Howe, R., Christensen-Dalsgaad, J., Hill, F., Komm, R. W., Larsen, R. M., Schou, J., Thompson, M. J., & Toomre, J. 2000, ApJ, 533, L163

Howe, R., Christensen-Dalsgaad, J., Hill, F., Komm, R. W., Larsen, R. M., Schou, J., Thompson, M. J., & Toomre J. 2000, Science, 287, 2456

Itoh, K., Itoh, S. -I., & Fukuyama, A. 1999, Transport and Structural Formation in Plasmas (Bristol: Institute of Physics)

Lang, K. R. 2001, The Cambridge Encyclopedia of the Sun (Cambridge: Cambridge University Press) Chapter 4.4

Parker, E. N. 1993, ApJ, 408, 707

Priest, E. R. 1982, Solar Magnetohydrodynamics (Dordrecht: Reidel)

Shibahashi, H. 2002, J. Plasma Fusion Res., 78, 497

Spiegel, E. A. & Zahn, J. -P. 1992, A&A, 265, 106

Thompson, M. J., et al. 1996, Science, 272, 1300

Tobias, S. M. 2003, in The Fluid Mechanics of Astrophysics and Geophysics, Vol. 12, ed. A. M. Soward & M. Ghil (London: Taylor and Francis), in press

Ulrich, R. K. 2001, ApJ, 560, 466

Vorontsov, S. V., Christensen-Dalsgaad, J., Schou, J., Strakhov, V. N., & Thompson, M. J. 2002, Science, 296, 101

Yoshizawa, A. 1990, Phys. Fluids, B 2, 1589

Yoshizawa, A., Itoh, S. -I., & Itoh, K. 2003, Plasma and Fluid Turbulence: Theory and Modelling (Bristol: Institute of Physics)

Yoshizawa, A., Kato, H., & Yokoi, N. 2000, ApJ, 537, 1039

Yoshizawa, A., Yokoi, N., Itoh, S. -I., & Itoh, K. 1998 Phys. Plasmas, 6, 3194

Yoshizawa, A, Itoh, S. -I., Itoh, K., & Yokoi, N. 2004, Plasma Phys. Contr. Fusion, 46, R25

Recent Issues of NIFS Series

NIFS-776 Y. Kondoh, M. Kondo, K. Shimoda, T. Takahashi and K. Osuga
Innovative Direct Energy Conversion Systems from Fusion Output Thermal Power to the Electrical One with the Use of Electronic Adiabatic Processes of Electron Fluid in Solid Conductors.
July 2003

NIFS-777 S.-I. Itoh, K. Itoh and M. Yagi
A Novel Turbulence Trigger for Neoclassical Tearing Modes in Tokamaks
July 2003

NIFS-778 T. Utsumi, J. Koga, T. Yabe, Y. Ogata, E. Matsunaga, T. Aoki and M. Sekine
Basis Set Approach in the Constrained Interpolation Profile Method
July 2003

NIFS-779 Oleg I. Tolstikhin and C. Namba
CTBC A Program to Solve the Collinear Three-Body Coulomb Problem: Bound States and Scattering Below the Three-Body Disintegration Threshold
Aug. 2003

NIFS-780 Contributions to 30th European Physical Society Conference on Controlled Fusion and Plasma Physics (St.Petersburg, Russia, 7-11 July 2003) from NIFS
Aug. 2003

NIFS-781 Ya. I. Kolesnichenko, K. Yamazaki, S. Yamamoto, V.V. Lutsenko, N. Nakajima, Y. Narushima, K. Toi, Yu. V. Yakovenko
Interplay of Energetic Ions and Alfvén Modes in Helical Plasmas
Aug. 2003

NIFS-782 S.-I. Itoh, K. Itoh and M. Yagi
Turbulence Trigger for Neoclassical Tearing Modes in Tokamaks
Sep. 2003

NIFS-783 F. Spineanu, M. Vlad, K. Itoh, H. Sanuki and S.-I. Itoh
Pole Dynamics for the Flierl-Petviashvili Equation and Zonal Flow
Sep. 2003

NIFS-784 R. Smirnov, Y. Tomita, T. Takizuka, A. Takayama, Yu. Chutov
Particle Simulation Study of Dust Particle Dynamics in Sheaths
Oct. 2003

NIFS-785 T.-H. Watanabe and H. Sugama
Kinetic Simulation of Steady States of Ion Temperature Gradient Driven Turbulence with Weak Collisionality
Nov. 2003

NIFS-786 K. Itoh, K. Hallatschek, S. Toda, H. Sanuki and S.-I. Itoh
Coherent Structure of Zonal Flow and Nonlinear Saturation
Dec. 2003

NIFS-787 S.I. Itoh, K. Itoh, M. Yagi and S. Toda
Statistical Theory for Transition and Long-time Sustainment of Improved Confinement State
Dec. 2003

NIFS-788 A. Yoshizawa, S.-I. Itoh, K. Itoh and N. Yokoi
Dynamos and MHD Theory of Turbulence Suppression
Dec. 2003

NIFS-789 V.D. Pustovitov
Pressure-induced Shift of the Plasma in a Helical System with Ideally Conducting Wall
Jan. 2004

NIFS-790 S. Koikari
Rooted Tree Analysis of Runge-Kutta Methods with Exact Treatment of Linear Terms
Jan. 2004

NIFS-791 T. Takahashi, K. Inoue, N. Iwasawa, T. Ishizuka and Y. Kondoh
Losses of Neutral Beam Injected Fast Ions Due to Adiabaticity Breaking Processes in a Field-Reversed Configuration
Feb. 2004

NIFS-792 T.-H. Watanabe and H. Sugama
Vlasov and Drift Kinetic Simulation Methods Based on the Symplectic Integrator
Feb. 2004

NIFS-793 H. Sugama and T.-H. Watanabe
Electromagnetic Microinstabilities in Helical Systems
Feb. 2004

NIFS-794 S.I. Kononenko, O.V.Kalantaryan, V.I. Muratov and C. Namba
Spectral and Angular Characteristics of Fast Proton-Induced Luminescence of Quartz
Mar. 2004

NIFS-795 K. Itoh, K. Hallatschek and S.-I. Itoh
Excitation of Geodesic Acoustic Mode in Toroidal Plasmas
Mar. 2004

NIFS-796 A. Shimizu, A. Fujisawa, S. Ohshima and H. Nakano
Consideration of Magnetic Field Fluctuation Measurements in a Torus Plasma with Heavy Ion Beam Probe
Mar. 2004

NIFS-797 M.I. Mikhailov, K. Yamazaki
Fast Particles Confinement in Stellarators with Both Poloidal-Pseudo-Symmetry and Quasi-Isodynamicity
Apr. 2004

NIFS-798 T. Takahashi, T. Kato, N. Iwasawa and Y. Kondoh
Power Deposition by Neutral Beam Injected Fast Ions in Field-Reversed Configurations
Apr. 2004

NIFS-799 V.S. Voitsenya, D.I. Naidenkova, Y. Kubota, S. Masuzaki, A. Sagara, K. Yamazaki
On the Possibility to Increase Efficiency of Conditioning of Vacuum Surfaces by Using a Discharge in a Hydrogen-noble Gas Mixture
Apr. 2004

NIFS-800 S.-I. Itoh, K. Itoh, A. Yoshizawa and N. Yokoi
Periodic Change of Solar Differential Rotation
May 2004