NASA-CR-193139

G-RANT
IN-92-CR
137378
P-17

Final Technical Report

NASA Grant NGL 05-020-272

Grant Period: 1971 -- 1990

Title: Physics of Solar Activity

P.I.: Dr. Peter A. Sturrock
Center for Space Science and Astrophysics
Stanford University

(NASA-CR-193139) PHYSICS OF SOLAR ACTIVITY Final Technical Report, 1971 - 1990 (Stanford Univ.) 17 p

N93-27114

Unclas

G3/92 0167878

Physics of Solar Activity

The NASA grant NGL 05-020-272 supported our research activity in Stanford University during the 20 year period from 1971 to 1990. We published 92 papers (72 in refereed journals) with the support by this grant. The aim of our research activity has been to increase our understanding of solar activity through data analysis, theoretical analysis, and computer modeling. Because our research subjects have been diverse and many researchers have been supported by this grant, it is impractical to describe in detail all the research activity supported by this grant. (The titles of the papers we have published will show the diversity of our research.) We will, therefore, select a few key areas of research and describe them in some detail.

(1) Energy Storage and Force-free Magnetic Field

The energy released during a solar flare is believed to be stored in magnetic fields. Because energy is stored gradually, it seems logical to assume that the magnetic field configurations have ample time to adjust to be "force free." Above the photosphere, especially in active regions, the magnetic forces tend to be much larger than thermal pressure gradient and gravitational forces acting on the plasma. Therefore, the magnetic field and electric current vectors must adjust to be very nearly aligned to make the unbalanced Lorentz forces negligible.

In this light, it is important to understand force-free magnetic field configurations. We have studied this problem early on (Barnes and Sturrock 1972; Barbosa 1976; Sturrock and Barbosa 1978), and we have recently developed a "magneto-frictional" method (Yang, Sturrock, and Antiochos 1986). Since then, we have applied this method to various cases

(Klimchuk, Sturrock, and Yang 1988; Klimchuk and Sturrock 1989; Klimchuk 1990).

In view of the important role of magnetic fields in solar activity, we have performed several studies on magnetic fields on the Sun (Sturrock 1972; 1978; 1980; 1987; 1990; 1991).

(2) Energy Release and Particle Acceleration

How the stored energy is suddenly released during a solar flare is the crux of solar flare physics. In this area, Dr. Sturrock has contributed many papers (Sturrock 1973; 1980; Sturrock et al. 1984; Sturrock 1986, Sturrock 1989a, b). It is known that a large fraction of the flare energy is channeled to accelerate particles (electrons and ions). The group has published several papers in this area (Newman et al 1971; Sturrock and Newman 1973; Barbosa 1976; Vlahos, Bai et al. 1986).

Dr. Sturrock has played a leadership role in organizing the Skylab Workshop on solar flares, which resulted in a book edited by him (Sturrock 1980). He also organized two workshops on solar flare prediction (Sturrock 1976; Antiochos, Bai, and Sturrock 1985).

(3) Radiation by Nonthermal Electrons

We deduce the number, energy spectrum, and total energy of energetic particles from the radiations they emit while interacting in the solar atmosphere. Therefore, research on the radiation processes is one of the main topics of solar flare physics. We have contributed several papers in this area (Chin, et al. 1971; Ramaty and Petrosian 1972; Sturrock and Epstein 1973; Petrosian 1973; Bai 1988).

(4) Coronal Loops

Skylab observations have shown that, except for coronal holes, the solar atmosphere is dominated by magnetic loops of various shapes and sizes. Solar flare energy is believed to be stored within magnetic loops or in the current sheets at boundaries between loops. Therefore, it is important to understand how magnetic loops and plasmas within them behave. Our group has done extensive research on this subject (Antiochos 1976, Antiochos and Sturrock 1976; Krall and Antiochos 1981; Antiochos et al. 1981, 1985).

(5) Flare Classification

Solar flares exhibit diverse phenomena including electromagnetic radiations ranging from radio waves to gamma rays with energies exceeding 100 MeV, ejection of plasmas and accelerated particles into interplanetary space, and generation of shock waves. However, we have found that flares do not always manifest all the phenomena associated with flares nor they exhibit random collections of flare phenomena. Instead, certain clusters of related phenomena tend to occur in the same flare. To understand the physical processes in solar flares, it is helpful to know which flare phenomena are related to which. From early on, we have noticed that gamma-ray line flares tend to show some characteristics not usually found in ordinary flares (Bai et al. 1985; Bai and Dennis 1985). A further study has shown that gamma-ray line flares are made of two kinds, impulsive and gradual GRL flares (Bai 1986a, b). Now interplanetary measurements show that the elemental abundances of energetic particles are different for different kinds of flare. Our studies on this subject were culminated by a review paper proposing a comprehensive flare classification scheme (Bai and Sturrock 1989).

(6) Longitude Distributions of Flares

Although solar flares are mainly coronal phenomena, the underlying cause of flares, the dynamo activity, is deep seated. If there is a spatial pattern in the dynamo activity, therefore, it would be borne out in the longitude distribution. From the early days, it was proposed that solar flare activity was concentrated in certain longitude bands. Earlier studies, however, were qualitative. We have studied longitude distributions of solar flares of cycle 19 in coordinate systems with arbitrary rotation periods, using the maximum likelihood method (Fung et al. 1971). This study showed evidence for an active longitude band rotating with a synodic period of 28.5 days.

Our recent interest in this subject was spurred by the discovery of the 154-day periodicity. By analyzing solar flares observed by instruments aboard SMM and GOES satellites and ground-based observatory, Bai (1987, 1988, 1990) has discovered two northern-hemisphere "hot spots" rotating with a synodic period of 26.73 days. A recent study including flares of cycle 22, shows that these hot spots remained at the same place for three solar cycles (cycles 20–22). For the first time, we have shown that hot spots last longer than one solar cycle. The cause of the hot spots is still unknown.

Bai (1988) has confirmed the hot spot with a rotation period of 28.5 days discovered by Fung et al. (1971) for cycle 19, but he has found that this hot spot was in the northern hemisphere. Therefore, the longitude distribution of the northern hemisphere flares must have re-organized after cycle 19, and two hot spots remained at the same places throughout cycles 20–22.

(7) Periodicities detected in the solar activity

The 154-day periodicity was discovered by Rieger et al. (1984), by analyzing the occurrence times of gamma-ray flares observed during 1980–1983. Since then, many people have confirmed the operation of this periodicity in different epochs. While most of the papers on this subject have remained in the discovery mode, we have contributed to the understanding of the cause of this periodicity. Not only have we confirmed the 154-day periodicity (Bogart and Bai 1985; Bai and Cliver 1990) but also discovered other related periodicities with periods at multiples of about 25.8 days (Bai 1987; Bai and Sturrock 1991; Bai 1992). Our study has eliminated the possibility of interacting hot spots being the cause of the 154-day periodicity (Bai and Sturrock 1987); and instead we have proposed that the Sun has a fundamental period of about 25.8 days and that periodicities of 51, 78, 102, 128, 154 days are its subharmonic periods (Bai and Sturrock 1991). Our recent study (Bai and Sturrock 1993) has found evidence for the fundamental clock mechanism.

We have also studied the methods of periodicity analysis (Sturrock and Shoub 1982; Bai 1992).

(8) Coronal Heating and Related Problems

The solar corona contains plasmas with temperatures around one million degrees. At first sight, it seems unreasonable that the 6000-degree photosphere can heat the million-degree corona. The coronal heating is still one of the unsolved problems in solar physics. We were interested in this problem from early on (Adams and Sturrock 1975), and have kept our interest (Antiochos and Underwood 1981; Sturrock and Uchida 1981; Antiochos and Sturrock 1982; Sturrock et al. 1990).

We have also studied spicules, surges, and prominences which may supply substantial energy to the corona (Antiochos 1980; Blake and Sturrock 1985; Antiochos and Klimchuk 1991).

(9) Plasma Processes

The solar atmosphere as well as more than 90% of the ordinary matter in the Universe is in the plasma state. Therefore, understanding of plasma processes is essential to understanding of high-energy phenomena in astrophysical objects. We have studied plasma processes in astrophysical objects including the Sun (Smith and Sturrock 1971; Sturrock et al 1971; Knight et al 1974; Antiochos and Sturrock 1976, 1978; Knight and Sturrock 1977; Shapiro and Knight 1978; Barbosa 1979; Krall and Antiochos 1980; Sturrock 1990, 1991).

(10) Other Areas

We have also contributed to other areas of solar physics (Moore and Fung 1972; Dingle et al. 1973; Antiochos and Underwood 1980; Antiochos 1984; Antiochos and Noci 1986; Klimchuk et al. 1991), to the influence of solar activity to terrestrial phenomena (Knight and Sturrock 1976; Lipa et al. 1976), and to extra-solar-system astrophysics (Antiochos et al. 1983; Sturrock 1986; Sturrock and Yang 1986).

Publications Supported by NASA Grant NGL 05-020-272

Newman, C.E., Sturrock, P.A., and Tademaru, E., 1971, *Astrophys. Space Sci.,* **10**, 102.

Particle flux associated with stochastic processes

Smith, D.F., and Sturrock, P.A., 1971, *Astrophys. Space Sci.*, **12**, 411.

Maximum temperatures for radiation from plasma waves

Fung, P.C.W., Sturrock, P.A., Switzer, P., and Van Hoven, G. , 1971, *Solar Phys.,* **18**, 90.

Longitude Distribution of Solar Flares

Chin, Y.C., Fung, P.C.W. and Lusignan, B.B., 1971, *Sol. Phys.* **16**, 135.

Polarization Measurements of Solar Type III Radio Bursts at 25.3 MHz

Sturrock, P.A., Fung, P.C.W., and Smith, D.F., 1971, *J. Plasma Phys.* **5**, 1.

A Weak Turbulence Analysis of the Two-Stream Instability

Sturrock, P.A., Jones, F.C., Newman, C.E., and Tademaru, E., 1971, *Astrophys. Sp. Sci.* **10**, 102.

Comments On the Formation of Energy Spectra in Synchrotron Sources

Sturrock, P.A., 1972, *Progress in Astro. and Aero*, **30**, 163.

Magnetic Models of Solar Flares

Sturrock, P.A., 1972, *Solar Physics*, **23**, 438.

A Classification of Magnetic Field Configurations Associated with Solar Flares

Barnes, C.W., and Sturrock, P.A., 1972, *Ap. J.*, **174**, 659.

Force-free Magnetic-field Structures and Their Role in Solar Activity

Moore, R.L., Fung, P.C.W., 1972, *Solar Phys.* **23**, 78.

Structure of the Chromosphere-Corona Transition Region

Petrosian, V., and Ramaty, R. R., 1972, *Astrophys. J.* **178**, 241.

Force-Free Absorption of Gyrosynchrotron Radiation in Solar Microwave Bursts

Sturrock, P.A., 1973, *Proc. Int. Conf. on Solar Terrestrial Relations*, (Calgary, Alberta, Canada: National Res. Council and U. of Calgary), p. 63.

Solar Flare Theory

Sturrock, P.A., 1973, *Proc. Symp. on High Energy Phenomena on the Sun*, (NASA SP-342), p. 3.

Mass Motion in Solar Flares

Dingle, L.A., Van Hoven, G., and Sturrock, P.A., 1973, *Solar Phys.,* **31**, 243.

Test for Planetary Influences in Solar Activity

Sturrock, P.A. and Roberts, D.H. and Turk, J.S., 1973, *Annals of the New York Academy of Sciences*, **224**, 206.

Magnetosphere Structure and Radiation Mechanisms of Pulsars

Sturrock, P.A., Epstein, R.I., 1973, *Astrophys. J.* **183**, 593.

Synchrotron Source I: Extension of Theory for Small Pitch Angles

Sturrock, P.A., Newman, C.E., 1973, *J. Math. Phys.* **14**, 502.

A Generalization of the Equations Governing the Evolution of a Particle Distribution in a Random Force Field

Petrosian, V., 1973, *Astrophys. J.*, **186**, 291.

Impulsive Solar X-Ray Bursts: Bremsstrahlung Radiation from a Beam of Electons in the Solar Chromosphere and the Total Energy of Solar Flares

Knight, J.W., Newman, C.E., and Sturrock, P.A., 1974, *Solar Phys.*, **37**, 183.

Two-fluid Model of the Solar Corona

Adams, W.M., and Sturrock, P.A., 1975, *Ap. J.*, **202**, 259.

A Model of Coronal Holes

Petrosian, V., 1975, *Astrophys. J.*, **197**, 235.

Impulsive Solar X-Ray Bursts: II. Statistical Correlation of Observations with Solar Longitude

Antiochos, S.K., 1976, SUIPR Report No. 679 (Ph.D. thesis),

Thermal Instability in Loop Prominence Systems

Antiochos, S. K., and Sturrock, P. A., 1976, *Sol. Phys.*, **49**, 359-367.

Influence of Magnetic Field Structure on the Conduction Cooling of Flare Loops

Barbosa, D.D., 1976, Solar Phys., 56, 55-66.

Linear Force-Free Fields in the Lower Corona

Knight, J.W., and Sturrock, P.A., 1976, *Nature*, **264**, 239.

Solar Activity, Geomagnetic Fields and Terrestrial Weather

Lipa, B.J., Barnes, C.W. and Sturrock, P.A., 1976, *Nature*, **259**, 302.

Search for Correlation between Ceomagnetic Disturbances and Mortality

Sturrock, P.A., et al., 1976, *Solar Phys.*, **46**, 411.

Report on the Solar Physics-Plasma Physics Workshop held at Stanford University, September 17-20, 1974

Knight, J.W., and Sturrock, P.A., 1977, *Ap. J.*, **318**, 306.

Reverse current in solar flares

Antiochos, S. K., and Sturrock, P. A., 1978, *Ap. J.*, **220**, 1137-1143.

Evaporative Cooling of Flare Plasma

Sturrock, P.A., Barbosa, D., 1978, *Astron. Astrophys.,* **62**, 267.

The Exterior Source Surface for Force-Free Fields

Shapiro, P. and Knight, J.W., 1978, *Astrophys. J.,* **224**, 1028.

The Rapid Heating of Coronal Plasma During Solar Flares: Nonequilibrium Ionization Diagnostics and Reverse Currents

Barbosa, D., 1979, *Astrophys. J.,* **228**, 909.

Dynamo Action in a Thin Slab

Barbosa, D., 1979, *Astrophys. J.,* **233**, 383.

Stochostic Acceleration of Solar Protons

Knight, J.W., Sturrock, P.A., and Schatten, K.H., 1979, *Ap. J. (Letters)*, **227**, L153.

A Sunspot Periodicity and Its Possible Relation to Solar Rotation

Antiochos, S.K., 1980, *Ap. J.*, **236**, 270-279.

A Model of Active Prominences

Antiochos, S.K., 1980, *Ap. J.*, **241**, 385-393.

Radiative Dominated Cooling of the Flare Corona and Transition Region

Antiochos, S. K., and Underwood, J. H., 1980, SUIPR Report No. 814.

The Minimum Flux Corona: Theory or Concept?

Krall, K. R., and Antiochos, S. K., 1980, *Ap. J.*, **242**, 374-382.

The Evolution of Active Region Loop Plasma

Sturrock, P.A., ed., 1980, Solar Flares: A Monograph from Skylab Solar Workshop, Boulder: University of Colorado Press.

Sturrock, P.A., and Stern, R., 1980, *Ap. J.*, **238**, 98-102.

Is the Galactic Corona produced by Galactic Flares?

Antiochos, S. K., 1981, Second Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, S.A.O. Special Report No. 392, Vol. II, , pp. 115.

The Differential Emission Measure of Dynamic Coronal Loops

Antiochos, S. K., Underwood, J. H., and Vesecky, J. F., 1981, *Solar Phenomena in Stars and Stellar Systems*, R. M. Bonnet and A. K. Dupree, eds. (Dordrecht: D. Reidel), p. 227.

Numerical Studies of the Energy Balance in Coronal Loops

Sturrock, P.A., and Uchida, Y., 1981, *Ap. J.*, **246**, 331.

Coronal Heating by Stochastic Magnetic Pumping

Antiochos, S. K., and Sturrock, P. A., 1982, *Ap. J.*, **254**, 343-348.

The Cooling and Condensation of Flare Coronal Plasma

Emslie, A.G., and Sturrock, P.A., 1982, *Solar Physics*, **80**, 99.

Temperature Minimum Heating in Solar Flares by Resistive Dissipation of Alfven Waves

Sturrock, P.A. and Shoub, E.C., 1982, *Ap. J.*, **256**, 788.

Examination of Time Series Through Randomly Broken Windows

Antiochos, S. K., Stern, R. A., and Underwood, J. H., 1983, *Ap. J. (Letters)*, **264**, L55-L59.

A Giant X-Ray Flare in the Hyades

Bai, T., 1983, Proc. 18th Intern. Cosmic Ray Conf. (Bangalore), **4**, 26.

Plausible Mechanisms for Rapid Acceleration of Protons During Solar Flares

Bai, T. Dennis, B.R., Kiplinger, A.L. Orwig,L.E., and Frost, K. J., 1983, *Sol. Phys.*, **86**, 401.

Characteristics of Gamma-Ray-Line Flares as Observed in Hard X-Ray Emissions and Other Phenomena

Antiochos, S. K., 1984, *Ap. J.*, **280**, 416-422.

A Dynamic Model for the Transition Region

Sturrock, P.A., Kaufmann, P., Moore, R.L., and Smith, D.F., 1984, *Solar Phys.,* **94**, 341.

Energy Release in Solar Flares

Antiochos, S.K., Bai, T., and Sturrock, P.A., 1985, Summary Proceedings of the Stanford Workshop on Solar Flare Prediction, (CSSA preprint).

Antiochos, S. K., Shoub, E. C., An, C.-H., and Emslie, A. G., 1985, *Ap. J.*, **298**, 876-886.

Thermal Stability of Static Coronal Loops: I. Effects of Boundary Conditions

Bai, T., & Dennis, B.R., 1985, *Ap. J.*, **292**, 699.

Characteristics of Gamma-Ray-Line Flares

Blake, M.L., and Sturrock, P.A., 1985, *Ap. J.*, **290**, 359.

Spicules and Surges

Bogart, R.S., & Bai, T., 1985, *Ap. J. (Letters)*, **299**, L51.

Confirmation of a 152-day Periodicity in the Occurrence Rate of Solar Flares Inferred from Microwave Data

Antiochos, S. K., and Noci, G., 1986, *Ap. J.*, **301**, 440-447.

The Structure of the Static Corona and Transition Region

Bai, T., 1986, *Adv. Space Res.* Vol. **6**, No. 6, p. 203.

Classification of Solar Flares and Phenomena Observed during the First and Second Phases of Flares

Bai, T., 1986, *Ap. J.*, **308**, 912.

Two Classes of Gamma-Ray/Proton Flares: Impulsive and Gradual

Bai, T., 1986, in *Solar Flares and Coronal Physics: Using P/OF as a Research Tool*, ed. E.A. Tandberg-Hanssen, R.M. Wilson, & H.S. Hudson, p.153.

Superactive Regions and Production of Major Flares

Sturrock, P.A., 1986, *Nature*, **321**, 47.

A Flare-Induced Cascade Model of Gamma-Ray Bursts

Sturrock, P.A., 1986, Rapid Fluctuations in Solar Flares, Proc. of Workshop held in Lanham, MD, Oct. 1985, eds. B. R. Dennis, L. E. Orwig, and A. L. Kiplinger, (NASA CP-2449), 1.

Rapid Fluctuations in Solar Flares

Sturrock, P.A. and Yang, W.H., 1986, Proc. IAU Symp. No. 119 on Quasars (Dordrecht: Reidel), 411-412.

Accretion Disk Magnetospheres

Sturrock, P.A., et al. 1986, Proc. Solar Terrestrial Prediction Workshop, Meudon, France, 1984 (Boulder, CO:NOAO and Bedford, MA: Hanscom Air Force Geophysical Lab.

Physical Aspects of the Prediction of Solar Flares

Vlahos, L., Bai, T., et al., 1986, Chapter 2 "Particle Acceleration" of Energetic Phenomenona on the Sun, the SMM Workshop Proceedings (NASA: Washington, DC).

Particle Acceleration

Yang, W.H., Sturrock, P.A., and Antiochos, S.K., 1986, *Ap J.*, **309**, 383.

Force-Free Magnetic Fields: The Magneto-Frictional Method

Bai, T., 1987, *Ap. J.*, **314**, 795.

Distributions of Flares on the Sun: Superactive Regions and Active Zones

Bai, T., 1987, *Ap. J. (Letters)*, **318**, L85.

Periodicity of the Flare Occurrence Rate in Solar Cycle 19

Bai, T., & Sturrock, P.A., 1987, *Nature*, **327**, 601.

On the 152-Day Periodicity of the Solar Flare Occurrence Rate

Sturrock, P.A., 1987, Artificial Satellites, V. 22, No. 1, (Polish Academy of Sci. Space Res. Ctr.: Polish Sci. Publishers), 57.

Physical Aspects of the Prediction of Solar Flares.

Sturrock, P.A., 1987, *Solar Phys.* **113**, 13.

Solar Flares and Magnetic Topology

Yang, W.H., 1987, Ph.D. Thesis, (Stanford University)

Non-Lienar Force-Free Magnetic Fields: Calculation and Application to Astronomy

Bai, T., 1988, *Ap. J.*, **328**, 860.

Distribution of Flares on the Sun during 1955-1985: 'Hot Spots' (Active Zones) Lasting for 30 Years

Bai, T., 1988, *Ap. J.*, **334**, 1049.

Directionality of Continuum Gamma Rays from Solar Flares

Klimchuk, J. A., Sturrock, P. A., and Yang, W.-H., 1988, *Ap.J.*, **335**, 456-467.

Coronal Magnetic Fields Produced by Photospheric Shear

Bai, T., 1989, in Max '91 Workshop #2, Developments in Observations and Theory for Solar Cycle 22, (June 8-9, 1989), ed. R.M. Winglee & B.R. Dennis, p. 46.

When and Where to Look to Observe Major Solar Flares

Bai, T., & Sturock, P.A., 1989, *Ann. Rev. Astron. Ap.*, **27**, 421.

Classification of Solar Flares

Klimchuk, J. A., 1989, *Solar Phys.*, **119**, 19-34.

Magnetic Properties of CIV Doppler Shift Patterns

Klimchuk, J. A., and Sturrock, P. A., 1989, *Ap. J.*, **345**, 1034-1041.

Force-Free Magnetic Fields: Is There a 'Loss of Equilibrium'?

Sturrock, P.A., 1989, Outstanding Problems in Solar System Plasma Physics: Theory and Instrumentation, AGU Monograph No. 54.

Energy Conversion in Solar Flares

Sturrock, P.A., 1989, *Solar Phys.* **121**, 387.

The Role of Eruption in Solar Flares

Bai, T. , 1990, *Ap. J. (Letters)*, **364**, L17.

Solar 'Hot Spots' are Still Hot

Bai, T. & Cliver, E. W., 1990, *Ap. J.*, **363**, 299.

A 154-Day Periodicity in the Occurrence Rate of Proton Flares

Bai, T., Cliver, E.W., & Kile, J. N., 1990, Proc. 21st Intern. Cosmic Ray Conf. (Adelaide), 5, 20.

A 154-Day Periodicity in the Occurrence Rate of Flares for Solar Cycle 19 through 21

Klimchuk, J. A., 1990, *Ap. J.*, **354**, 745-754.

Shear-Induced Inflation of Coronal Magnetic Fields

Sturrock, P.A., 1990, *Ap.J.*, **380**, 655-659.

Maximum energy of semi-infinite magnetic field configurations

Sturrock, P.A., Dixon, W.W., Klimchuk, J.A., and Antiochos, S.K., 1990, *Ap. J. (Letters)*, **356**, L31-L34.

Episodic Coronal Heating

Antiochos, S. K., and Klimchuk, J. A., 1991, *Ap. J.*, **378**, 372-377.

A New Model For the Formation of Solar Prominences

Bai, T., & Sturrock, P.A., 1991, *Nature*, **350**, 141.

The 154-Day and Related Periodicities as Subharmonics of a Fundamental Period

Klimchuk, J. A, Canfield, R. C., and Rhoads, J. E., 1991, Flare Physics in Solar Activity Maximum 22, (eds. Y. Uchida, R. C. Canfield, T. Watanabe, E. Hiei; Berlin: Springer-Verlag), p. 219-223.

The Practical Application of the Magnetic Virial Theorem

Sturrock, P.A., 1991, *Lecture Notes in Physics* **387**, Flare Physics in Solar Activity Maximum 22 (eds. Y. Uchida, R.C. Canfield, T. Watanabe and E. Hiei; Berlin, Springer), pp. 224-227.

Maximum Energy of Semi-Infinite Magnetic Field Configurations.

Bai, T., 1992, *Ap. J.* **397**, 584.

Methods of Periodicity Analysis: Relationship between the Rayleigh Analysis and a Maximum Likelihood Method

Note: The papers are ordered chronologically. Within the same year, they are ordered alphabetically in authors' names. The total number of papers is 92, of which 72 are papers published in refereed journals.