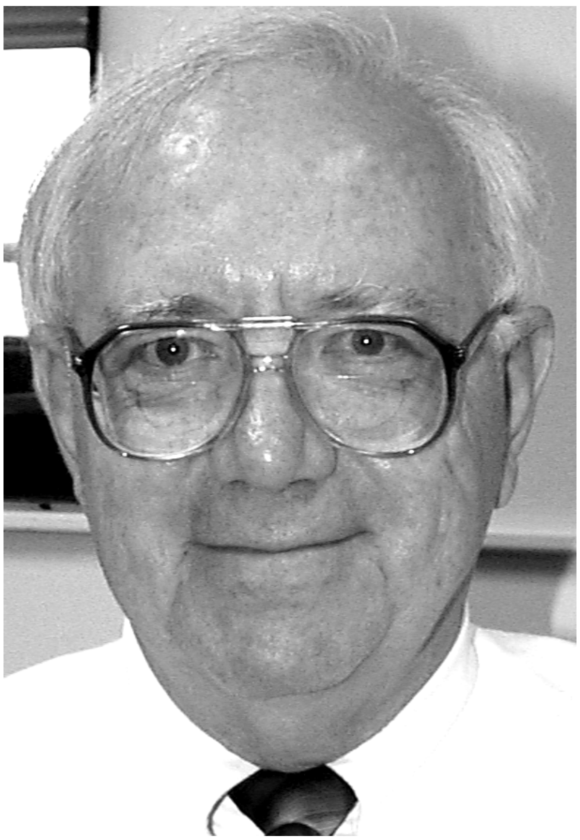
GMAG NEWSLETTER

A Focused Group within The American Physical Society

Issue N^0 11, August 2002, Edited by R Bruce van Dover

A Note from the Chair



I am delighted to introduce this newsletter and tell you about ways you can and should get involved in GMAG. Magnetism and its Applications is one of the most dynamic fields of physics and the economic impact of the field, some $100 billion annually, serves to strengthen our research and educational activities.

An important function of GMAG is to plan and organize sessions in our field at the March APS Meeting. This is done by sponsoring focus topics, by organizing invited symposia, and by carrying out the sorting of contributed abstracts for category 6 (see the listing in this Newsletter). The focus topics are arranged into individual sessions which typically have one invited speaker and up to 12 contributed talks. For the March 2003 Meeting GMAG is co-sponsoring the following five focus topics, described in further detail below:

2.9.2 Spin-Dependent Phenomena in Semiconductors

6.11.1 Theory and Simulation of Magnetism and Spin Dependent Properties

6.11.2 Magnetic Nanostructures and Heterostructures

6.11.3 Magnetoresistive Oxides

6.11.4 Spin Transport and Spin Dynamics in Metal-Based Systems

Full descriptions, organizers and contact information for each topic are listed below. Suggestions for invited speakers for each of these topics are encouraged and should be made directly to the organizers by 30 August. **Note**: contributed talks are still to be submitted by Dec. 6 directly to APS at http://abstracts.aps.org/ following their procedures. Use the sorting categories above if your contributed talk fits into one of these. Sending an additional copy of your abstract to one of the organizers is encouraged but not required.

In addition to these focus topics, GMAG is allocated three Invited Symposia slots to organize for the meeting. We often arrange to co-sponsor one of these symposia which another Division of APS, which allows us to increase this number. This year's GMAG Program Chair, also the Chair-Elect of GMAG, is Frances Hellman. Please contact Frances fhellman@ucsd.edu no later than Sept. 15 with suggestions for Invited Symposia.

APS Fellowship nominations are not due until the Spring, and we will give you further information closer to the deadline date. However, now is a good time to begin thinking about candidates, nominators, etc. The GMAG Fellowship Chair (also the Vice Chair) is Peter Schiffer, and the members of the Fellowship Committee are the Executive Committee Members. Also, please be sure to nominate worthy candidates from our magnetism community for the various APS prizes and awards (see APS web site for information on how to do this).

I urge you to get involved with the activities of GMAG through its APS meeting organization and in other ways. Also, please write or call me if you have suggestions for ways GMAG can benefit our discipline and its members.

-Dave Sellmyer

GMAG-sponsored Focus Topics for March 2003

Magnetic Nanostructures and Heterostructures (DMP/GMAG) -- 6.9.1

This session will be focused on the properties of artificial magnetic structures characterized by reduced dimensions at the nanometer length scale. Types of structures include films, superlattices, multilayers, nanocomposites, heterostructures, spin valves, tunnel junctions, exchange-spring magnets, wedges, nanowires, magnetic point contacts, quantum dots, particle arrays and patterned films. These magnetic structures may be composed, for example, of metals, insulators, magnetic semiconductors, half metals, perovskites or intermetallic compounds. This session will cover experimental and theoretical advances in low-dimensional magnetism, interlayer magnetic coupling, exchange bias, spin-dependent transport (especially giant magnetoresistance, tunneling magnetoresistance and spin injection), magnetic quantum confinement, magnetic anisotropy, effects of structural disorder, and other magnetic phenomena. Of special interest are the fabrication of nanostructures with atomic-scale control, high-resolution characterization methods with site and/or element specificity, novel techniques for the creation of nanoscale magnetic features, and unusual physical phenomena present in these systems.

Organizers:

Julie Borchers
NIST Center for Neutron Research
100 Bureau Drive
Bldg. 235, Stop8562
Gaithersburg, MD 20899-8562
Tel: 301-975-6597
Fax: 301-921-9847
email: julie.borchers@nist.gov

Liesl Folks
IBM Almaden Research Center
Building 080 / K66 / C3-414
650 Harry Road
San Jose, CA 95120-6099
Tel: 408-927-2269
Fax: 408-927-2100
email: liesl@almaden.ibm.com

Shufeng Zhang
Department of Physics
University of Missouri-Columbia
Columbia, MO 65212
Tel: 573-882-5372
Fax: 573-882-4195
email: zhangshu@missouri.edu

Magnetoresistive Oxides **(DMP/GMAG) –** 6.9.1

Mixed-valent manganese oxides known as colossal magnetoresistive (CMR) manganites exhibit a dramatic interplay among spin, charge, lattice, and orbital degrees of freedom. The result is a spectacular array of competing ground states that include ferromagnetic metals, antiferromagnetic insulators, charge- and orbital ordered states, and micro- and mesoscopic phase mixtures of these states. This focus topic will address fundamental aspects of such multiple ground states in manganites and related transition metal oxides (ruthenates, cobaltates, etc.). Contributions will include both experimental and theoretical studies of chemical, structural, and physical properties, emphasizing the static and dynamic aspects of magnetic, charge, and orbital ordering, the role of inhomogeneity on varying length scales, field-induced phenomena, and phase segregation. This focus topic will bring together wide-ranging efforts in the manganites and related transition metal oxides to highlight and unify the understanding of their fundamental physics.

Organizer*s:*

Professor Takeshi Egami
Department of Materials Science and Engineering
University of Pennsylvania

LRSM, 3231 Walnut Street
Philadelphia, PA 19104-6272
Tel: 215-898-5138
Fax: 215-573-2128
e-mail: egami@seas.upenn.edu

Dr. John F. Mitchell
Materials Science Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Tel: 630-252-5852
Fax: 630-252-7777
e-mail: mitchell@anl.gov

Professor Peter Schiffer
Department of Physics
Pennsylvania State University
0104 Davey Laboratory
University Park, PA 16802
Tel: 814-865-5982
Fax: 1-814-865-3604
e-mail: schiffer@phys.psu.edu

Brief Tutorial

—This article presents an authoritative introduction to the physics and modelling of hysteresis in magnetic materials. We present it with the expectation that it will provide a perspective that is useful to researchers engaged a wide range of topics in magnetism. Was it useful to you? Please send feedback, as well as suggestions for future articles, to the newsletter Editor, R Bruce van Dover, email: rbvd@mailaps.org.

Download tutorial pdf

Non-linear magnetism and hysteresis on length scales from the atomistic to the macroscopic

D.C. Jiles, Ames Laboratory, Iowa State University

Development of model theories of hysteresis

When materials are exposed to high levels of external magnetic field the response of materials eventually extends beyond the simple linear regime. Under these conditions it is found that the change in response of the materials is no longer reversible. These phenomena are well documented in the experimental literature. However the theoretical non-linear description of the response of materials is only at a very early stage of development compared with the low amplitude linear/reversible model theories.

Hysteresis is a commonly-occurring phenomenon in nature arising most often as a result of cooperative behaviour of a large number of identical interacting elements [1]. The most familiar examples occur in ferromagnetism, but similar behavior occurs in ferroelectrics [2], ferroelastics [3] and fatigue. For a long time theory and modelling of hysteresis in magnetic materials was a subject for the specialist investigator. However in recent years the widespread, and increasing capability and accessibility of computers has made modelling available to a much wider range of investigators, so that this area of study has become of much wider interest.

The magnetic moment per unit volume can be represented in terms of a net magnetic moment per atom, although in many cases, but not all, the magnetic moment is not actually localized on the atomic/ionic cores, but instead is caused by itinerant electrons. To understand how this net magnetic moment comes about theories were developed by Stoner [4] and Slater [5] concerning the electron band structure of magnetic materials, which explained why there is an imbalance of spin up and spin down electrons in ferromagnets. Band structure calculations provide a description of magnetism at a very fundamental level and much work is still being performed to refine and develop band structure calculations [6].

Magnetism at the discrete level of individual atoms and beyond to the continuum level

The principal idea of the Landau-Lifschitz-Gilbert model is to describe the behavior of individual discrete magnetic moments under the action of a magnetic field. Clearly from the classical times of Ampere it was known that on the macroscopic scale a magnetic dipole moment of fixed magnitude would rotate under a magnetic field. This same concept, the general torque equation, was applied at the atomistic scale, or more correctly at the level of discrete magnetic moments of fixed magnitude but variable orientation, by Landau and Lifschitz [7]. This approach can be used to describe the behavior of an individual magnetic moment. The behavior of the entire material can then be determined by integrating the same process over the entire solid. The rate of change of magnetization with time then depends on the torque

$$\frac{\partial M}{\partial t} = -\gamma_r \tau = \mu_o m \times H \qquad (1)$$

In the absence of damping a magnetic moment that is not initially aligned with the total field will precess around the field direction with a resonance frequency $\omega_o = \gamma_r \mu_o H$

where is the gyromagnetic ratio of the magnetic moment. In the complete absence of damping this precession will continue for infinite time. In practice there is always some damping in solids and therefore for light damping (long time constant) there will be some precessional motion, and some rotational motion towards the field direction. The time taken to do this will depend on the damping coefficient. At high levels of damping (short time constant) the precessional component of the motion is suppressed because the moment reaches its final equilibrium orientation before precession has taken place.

In a magnetic material there are interactions between the moments, so that magnetism in solids is a cooperative process. Therefore the above equation must be modified when dealing with moments in a solid to take into account these interactions. Landau and Lifschitz suggested the following modification

(2)

Where the second term on the right hand side of the equation is a damping term which restrains the rotation of the moments under the action of a field. The existence of this damping term was, and remains, a hypothesis. There is no direct experimental verification, but the existence of such a term in bulk materials is reasonable from a theoretical standpoint.

The results of calculations based on the Landau-Lifschitz-Gilbert model can be averaged to provide hysteresis curves of materials. The model can be extended beyond the range of the single domain into simulations of multi-domain specimens through the use of finite element methods. This approach is known as "computational micromagnetics" and enables both micro- and macro-scale calculations to be incorporated into a single model simulation [8, 9].

Magnetism of domain rotation

The Stoner-Wohlfarth model takes as its basis an array of single-domain particles which can reorient their magnetization by coherent rotation of all moments within the domain. As such it takes no account of the details of the individual moments below the single domain in scale and does not try to account for the orientations within the domain. Within domains the model considers the competing effects of anisotropy and magnetic field on the orientation of moments. The domains themselves can have random alignments or they can be textured (meaning preferred orientation) or they can be even completely aligned in certain directions, although this would be a relatively trivial case requiring nothing more than a calculation of moment orientations within one single domain particle.

The model in its original formulation assumed that there were no magnetic interactions between the particles. In other words the distribution of the particles was so dilute that each particle was effectively isolated could not be influenced by the orientation of any other particles. This assumption can be changed, and has been changed by others, although including such interactions adds greatly to the computational complexity of the model. The model in its original condition also assumed axial anisotropy. This is the simplest type of anisotropic calculation to make. Other forms of anisotropy such as cubic can be included [10].

The basic idea of the model is to consider the reorientation of a magnetic moment within a single domain particle in which the applied field is at some arbitrary angle to the anisotropic easy axis. In the case of the uniaxial easy axis along the field direction, this results in a bimodal switching behavior with attendant coercive fields in the forward and reverse directions. In the other extreme case, where the magnetic field is applied along the anisotropic hard axis this results is a magnetization curve with no coercivity. In general the domains will be oriented at an arbitrary angle relative to the field and such domains will have properties that lie between these two extremes. A complete material may then consist of an assembly of domains, each at different angles to the field direction. The overall magnetization of the multidomain sample is then the vector sum of all of the magnetic moments of the domains divided by the total volume.

The turning force on a magnetic moment due to the applied field depends on the vector product of magnetic moment with magnetic field. The turning force on the magnetic moment due to anisotropy is the derivative of the energy with respect to angle. From the Stoner-Wohlfarth model it is possible to calculate the saturation field H_s needed to rotate the magnetization of the most difficult domain oriented at 90^o to the field direction,

(3)

It is also possible to calculate the coercivity of the domains based on the switching field needed to reorient the domain aligned antiparallel to the field,

(4)

The model has been widely used for describing the magnetic properties of materials on anisotropy and texture. In addition many of the original ideas behind the model have been developed and extended and have found applications in fine particle systems. [11, 12].

Magnetism of domain boundary motion

Although in most cases the boundaries of magnetic domains comprise only a small fraction of the total volume of a magnetic material, in multi-domain samples much of the magnetization change occurs in these regions and therefore it is of great interest to know and understand what changes are occurring at the boundary in order to predict and model the properties of such materials. The importance of domain boundary motion has been recognized by many investigators including Becker [13], Kersten [14, 15], Neel [16, 17], Globus [18-23] and Bertotti [24, 25]. The main idea in the treatment of domain boundary motion is to separate the motion into two components: reversible and irreversible. In most respects this separation is somewhat artificial, since both processes take place together in multi-domain materials. However the physics of the situation can be more easily analysed if these processes are separated. Irreversible processes necessarily cause energy dissipation and lead to coercivity and hysteresis while reversible processes do not.

The most comprehensive treatment of the underlying theory of the Globus model has been given by Escobar et al. [26, 27]. Accordingly the initial susceptibility due to domain wall bending is

(5)

where M_s is saturation magnetization, is the domain wall surface energy and D is the grain diameter. The value of the critical field for the unpinning of domain walls is:

(6)

where f is the pinning force per unit length on the domain wall along the grain boundary, which is assumed to be independent of the applied field.

Magnetism at the macroscopic scale: the integration of single domain switching processes

The Preisach model is a general mathematical model which describes hysteresis on the macroscopic scale [28]. The model was first developed to treat magnetic hysteresis but the mathematical structure is equally applicable to other physical systems exhibiting hysteresis, such as ferroelectric or mechanical hysteresis. The model treats magnetic hysteresis as simply a summation of a large number of microscopic switching events occurring in a magnetic material. It was actually a development of previous work on hysteresis by Weiss and Freudenreich and also derives some of its ideas from the earlier model of Ising.

The Preisach model describes materials as an array of domains each with the same magnetic moment per unit volume (magnetization), but with different switching fields. The allowed microstate of the magnetic moment is either "up" or "down", as in the Ising model. This spin up and spin down restriction does limit the relevance of the model to actual physical reality in most magnetic materials. The domains in the Preisach model remain the same size, but there is no fundamental problem with this approach for empirical modelling since the volume fractions of the domains with particular combinations of switching fields can be varied within the model.

The magnetic characteristics of a material are represented as the volume fraction of domains with particular combinations of switching field. This is described by probability distribution function $P(h_a,h_b)$ over the Preisach plane defined by all possible combinations of h_a and h_b, which is the span of values of the two switching fields [29]. The probability density function (also known as the Preisach function) P varies over the span of possible values of switching fields and this represents the distribution of different types of domain in the material. The magnetization *M* of the system as a function of applied field H(t) can be calculated by integration [30] from the equation

(7)

where is saturation magnetization. The value of is either +1 or –1 depending on the magnetic history. As a result the magnetization is path dependent exhibiting hysteresis which is dependent on the sequence of switching field strengths.

Magnetism at the multidomain level

In dealing with the behavior of materials, in particular their bulk magnetic properties such as coercivity, remanence, permeability and hysteresis loss, other problems arise that make it difficult if not impossible to simply scale up the predictions of models that are based on consideration of one or two domains. Therefore a more general approach is needed in order to develop equations that represent the average behavior of the materials. These models necessarily use statistical thermodynamic principles to describe the resulting magnetization behavior of a very large number of magnetic domains.

The earliest thermodynamic approaches were developed for the simplest systems, specifically paramagnets. Paramagnets have the simplicity of being magnetically homogeneous, unlike ferromagnets. Later models were developed for the more technically important class of ferromagnets without including hysteresis, and finally hysteresis models were developed. These type of models depends on statistical mechanics and is most relevant on the mesoscopic scale. It works well for materials with low anisotropy for which the main mechanism is domain boundary movement. It can be used for simple anisotropies such as axial and planar anisotropies with minor modifications. For highly anisotropic materials it can still be used with the understanding that a simple analytic anhysteretic equation can not in general be developed for anisotropic materials and therefore the mathematical approximations become less realistic the greater the anisotropy and the larger the number of magnetic easy directions.

The classical model for magnetism is the Langevin-Weiss model which considers an array of magnetic moments in thermal equilibrium at a particular temperature. This was used by Jiles and Atherton [31] as the basis for developing a model of hysteresis. The orientations of the magnetic moments are distributed statistically and integrating the distribution of moments over all possible orientations leads to an equation for the bulk magnetization. The details of this depend on the restrictions imposed by anisotropy, so that for example different solutions are obtained depending on whether the magnetic moments experience axial anisotropy, planar anisotropy or are in a completely isotropic environment [32].

The extension of the Langevin-Weiss theory used to describe ferromagnetic materials, incorporates a coupling among magnetic moments acting as a strong magnetic field to align the magnetic moments in a domain parallel to each other. To quantify this coupling a mean field which is proportional to the bulk magnetization, is used. This mean field approach to describing the interactions needs to be applied with some caution, but recent work by Chamberlin [33] has shown that the mean field approach is viable for clusters of spins on the nanoscopic scale.

By replacing the classical magnetic field H with the effective magnetic field H + M, which includes coupling to the magnetization, an equation for the anhysteretic magnetization of a ferromagnetic material can be obtained as follows.

(8)

Instead of considering coupling between each individual magnetic moment the mean field is used to represent the inter-domain coupling. For isotropic materials the anhysteretic function is

(9)

where and . Alternatively for materials exhibiting axial anisotropy,

(10)

From this description of the thermodynamic anhysteretic magnetization it is possible to develop a description of hysteresis through consideration of energy dissipation mechanisms. The irreversible and reversible components of magnetization can be described separately in the mathematics, although they are linked physically. The two components of magnetization can then be combined to give an equation for the total magnetization.

Conclusions

High performance computing is enabling researchers to model magnetic devices at smaller and smaller length scales, while at the same time accurate first principles calculations of magnetic properties now extend to systems involving thousands of atoms. The two different approaches, continuum versus discrete, are approaching each other at the nanoscopic length scales. Model theories have been developed to describe the properties of magnetic materials at length scales beginning from the atomistic through micromagnetics, macroscopic Preisach, domain rotational models and model theories of domain wall motion.

References

[1] T. Vicsek, "A question of scale," *Nature* 411, pp. 421, 2001.

[2] P.J. Chen and S.T. Montgomery, "A macroscopic theory for the existence of the hysteresis and butterfly loops in ferroelectricity," *Ferroelectrics*, vol.23, (no.3-4), pp.199, 1980.

[3] J.A. Tuszynski, B. Mroz, H. Kiefte, M.J. Clouter, "Comments on the hysteresis loop in ferroelastic $LiCsSO_4$," *Ferroelectrics*, vol.77, Jan. 1988. p.111-20

[4] E.C. Stoner, Phil. Mag. 15, 1080, 1933.

[5] J.C.Slater, Phys. Rev. 49, 537, 1936

[6] V.Antropov, B.N.Harmon and G.M.Stocks, Phys. Rev. B, 54, 1019, 1996.

[7] L.D.Landau and E.M.Lifschitz, Phys.Z. Sowjetunion, 8, 153, 1935

[8] H.Kronmuller, R.Fischer, R.Hertel and T.Leineweber, J.MMM. 175, 177, 1997.

[9] J.Fidler and T.Schrefl J.Phys. D. 33, R135, 2000.

[10] E.W.Lee and J.E.L.Bishop, Proc. Phys. Soc. (Lond.), 89, 661, 1966.

[11] G.W.D.Spratt, P.R.Bissell, R.W.Chantrell and E.P.Wohlfarth, J.MMM 75, 309, 1988.

[12] R.W.Chantrell, *'Hysteresis particulate materials'* in "*Magnetic Hysteresis in Novel Magnetic Materials*", G.C.Hadjipanayis, Kluwer, Dordrecht, 1997.

[13] R. Becker , Phys. Zeits. 33, 905, 1932

[14] M. Kersten, *"Underlying theory of ferromagnetic hysteresis and coercivity"*, Hirzel, Leipzig, 1943

[15] M. Kersten, Zeits. Angew. Phys. 8, 496, 1956

[16] L. Neel, J. de Phys. et Radium, 5, 18, 1944

[17] L. Neel, J. de Phys. et Radium, 20, 215, 1959

[18] A. Globus, Comptes Rendus Acad. Seances 255, 1709, 1962

[19] A. Globus and P. Duplex, IEEE Trans. Mag. 2, 441, 1966.

[20] A. Globus and P.Duplex, Phys. Stat. Sol. 31, 765, 1969.

[21] A.Globus, P.Duplex and M.Guyot, IEEE Trans.Mag., 7, 617, 1971.

[22] A.Globus and M.Guyot, Phys.Stat. Sol. B 52, 427, 1972.

[23] A.Globus and M.Guyot, Phys.Stat. Sol. B 59, 447, 1973.

[24] G.Bertotti, IEEE Trans.Mag. 24, 621, 1988.

[25] B. Alessandro, C.Beatrice, G. Bertotti and A. Montorsi, J.Appl.Phys. 68, 2901, 1990.

[26] M.A.Escobar, R.Valenzuela and L.F.Magana, J. Appl.Phys. 54, 5935, 1983.

[27] M.A.Escobar, L.F.Magana and R.Valenzuela, J. Appl. Phys. 57, 2142, 1985.

[28] I.D. Mayergoyz, *Mathematical models of hysteresis,* New York, Springer-Verlag, New York, 1991.

[29] G.Bertotti, "*Hysteresis in Magnetism*", Academic Press, San Diego, 1998.

[30] G.Bertotti , I.D.Mayergoyz, V.Basso and A.Magni, "Functional integration approach to hysteresis", Phys. Rev E., 60, 1428, 1999.

[31] D.C. Jiles and D.L.Atherton, J.Mag.Mag.Mater., 61, 48, 1986.

[32] D. C. Jiles, S. J. Lee, J. Kenkel, K. L. Metlov, "Superparamagnetic magnetization equation in two dimensions," *Appl. Phys. Lett.* 77, 1029, 2000.

[33] R.V.Chamberlin, Nature, 408, 337, 2000.

GMAG Officers

Chair Members at Large of the Executive Committee (Term ends March xxxx)

David Sellmyer *dsellmyer1@unl.edu* Jim Rhyne (2002) *jrhyne@showme.missouri.edu*

Ivan Schuller (2002) *ischuller@ucsd.edu*

Chair-Elect Richard Watson (2003) *watson@cmt5.phy.bnl.gov*

Frances Hellman *fhellman@ucsd.edu* Barbara Jones (2004) *bajones@almaden.ibm.com*

Jack Bass (2004) *bass@pa.msu.edu*

Vice-Chair

Peter Schiffer

Secretary-Treasurer

R Bruce van Dover *rbvd@agere.com*

Past Chair

Jeff Lynn j*eff.lynn@nist.gov*

Si Foner *sfoner@mit.edu*

Lawrence Bennett *lbennett@seas.gwu.edu*

Carl Patton *patton@lamar.colostate.edu*

David Jiles *gauss@ameslab.gov*

Standing Committees:

Nominating Committee (appointed by GMAG Chair):

Barbara Jones (Chair) *bajones@almaden.ibm.com*

Jack Bass *bass@pa.msu.edu*

Sam Bader *bader@anl.gov*

Art Ramirez (APS Council Member) *aramirez@lanl.gov*

Fellowship Committee:

(GMAG Bylaws specify that the GMAG Vice-Chair be the Chair of the Fellowship Committee)

(The recent amendment to the Bylaws specifies that the Executive Committee Members also serve on the Fellowship Committee)

Frances Hellman (Chair) *fhellman@ucsd.edu*

Executive Committee

Program Committee (by formal convention Chair-Elect serves as Chair of the Program Committee):

David Sellmyer *dsellmyer1@unl.edu*