# Seminal advances in science
# by UAH Scientist Dr. Gary P. Zank
# Member of the National Academy of Sciences

Dr. Gary P. Zank's research interests are in space physics and astrophysics. He has made numerous seminal advances in 1) the understanding of the interaction of the solar wind with the interstellar medium, 2) turbulence and waves in the solar wind, 3) the acceleration of particles at shock waves, and their subsequent transport throughout the heliosphere, 4) the physics of shock waves, and 5) the interaction of the solar wind with the non-magnetized bodies.

Dr. Zank's current *h-factor* is 62, with ~ 13,365 citations, of which 1350 were in 2015 alone, according to Google Scholar. 13 papers have more than 200 citations and 34 have been cited 100 or more times. A brief summary of the impact of some of Zank's reseaerch follows.

***Solar Wind – Local Interstellar Medium (LISM) Interaction:*** Ian Axford in his 1972 review laid out our understanding of the interaction of the solar wind with the local interstellar medium for the next 25 years. It was only from 1995 that the new paradigm that is used today was laid out in three papers by Baranov and Malama 1993, Pauls, Zank & Williams, 1995, and Zank, Pauls, Williams, and Doyle 1996. These three papers, using quite distinct approaches, established that the physics of the solar wind in the outer heliosphere, beyond some 10 AU, was dominated by the charge-exchange interaction of neutral interstellar Hydrogen with the solar and interstellar plasma. These papers established the critical importance of coupling the evolution of the neutral H distribution with that of the magnetized plasma. These three papers have completely dominated the development of the field since, and they and subsequent papers based on our formulation form our theoretical understanding of the observations returned by Voyager 1 and 2 and the IBEX mission. This work represented a complete paradigm shift and one that will endure as the fundamental description of the global heliosphere.

In elucidating the physics of the solar wind – Local Interstellar Medium (LISM), Dr. Zank and his colleagues utilized a combination of very sophisticated numerical codes, analytical modeling and testing against observations (some of which, such as Lyman-alpha absorption measurements, were not hitherto part of the traditional observational tools used by space physicists).

Besides laying down the basis for our understanding of the large-scale heliosphere, Dr. Zank also made a number of very specific and important predictions that have subsequently been verified observationally.

***Hydrogen wall***: Our models predicted the existence of the hydrogen wall, a region of heated, compressed neutral interstellar hydrogen adjacent to and beyond the heliopause. The fortuitous discovery a few years later by Jeff Linsky and Brian Wood of unexplained Lyman-alpha absorption in Hubble GHRS spectra in the upwind direction was interpreted as evidence for the existence of the hydrogen wall. Dr. Zank and colleagues then showed explicitly that the Ly-alpha absorption measurements could be fitted to spectra derived from global heliospheric models, which included the physics of the interaction between plasma and neutral interstellar hydrogen.

In addition, we established the possibility of using such measurements to (1) place constraints on the global structure of the heliosphere, and (2) infer the existence and properties of hitherto unobservable stellar winds from neighboring sun-like stars. Much of this and related work is summarized in a large review which has become the standard reference on the subject (more than 400 citations). Dr. Zank's prediction and discovery of the hydrogen wall, a major boundary and feature of the heliosphere, is regarded by many in the space physics community as one of the major discoveries of the past decade.

***Termination shock structure:*** Of particular importance was the discovery by Voyager 2 that one of the heliospheric termination shock crossing revealed an almost classical perpendicular shock structure. However, plasma measurements revealed that the solar wind protons were not responsible for the basic dissipation process – instead, pickup ions provided the primary dissipation mechanism. The Voyager 2 observations were a major surprise to many but this had in fact been predicted by Dr. Zank and his colleagues(Pauls, Cairns, and Webb) in 1996. Rather remarkably, IBEX has since made measurements that support this interpretation based on measurements of energetic neutral atoms at 1AU and this new interpretation of the multi-component nature of the inner heliosheath plasma and the outer heliosheath plasma is now becoming the accepted paradigm for the boundaries of our heliosphere.

***IBEX ribbon:*** A surprising discovery by the IBEX mission was the so-called "ribbon" – a localized region of enhanced energetic neutral atom flux in the form of a ribbon across the sky. It was recognized that the most recent MHD global models developed by Dr. Zank and colleagues showed that the ribbon location could be specified by the region of the sky that corresponded to the section of the draped interstellar magnetic that was orthogonal to the radial coordinate centered on the Sun. They developed a theoretical model that was then incorporated into our global heliospheric models to explain the ribbon. The model was based on the secondary ionization and subsequent re-neutralization of neutrals created in either the hot heliosheath or fast (supersonic) solar wind, and can successfully reproduce the observed ribbon. The model that we advanced (Heerikhuisen et al., 2010) forms the basis for the explanation of the ribbon.

***Turbulence:*** This is an area to which Dr. Zank contributed quite a lot in quite an important and far-reaching way. His efforts in this field began by developing a model to explain an enduring observational puzzle, which was that measurements of density fluctuations in the solar wind and interstellar medium using radio scintillation observations showed that the density spectrum exhibited a Kolmogorov-like spectrum across decades of wave number space (from parsecs to 100's of meters). Specifically, Dr. Zank developed the theory of *nearly incompressible MHD* (NI MHD), motivated by an earlier suggestion by David Montgomery to explain the observed universal Kolmogorov-like power law spectrum of (electron) density fluctuations. This work showed explicitly and constructively the connection between compressible and incompressible fluids, including MHD, and was thus of immediate importance to our understanding of solar wind fluctuations, which appear to exhibit characteristics of both descriptions at different times. Two major predictions emerged from the NI MHD theory, both of which have been tested observationally. The first is the prediction of two classes of MHD in the NI MHD limit, heat conduction dominated and heat conduction modified, for which distinct scalings and correlations hold for fluctuating variables such as density, temperature, etc., and for which distinct classes of Pressure Balanced Structures (PBSs) are predicted. Solar wind observations have verified the existence of the predicted scalings, correlations and PBSs. The second, and perhaps most important, result from NI MHD is the discovery that for plasma beta conditions corresponding to either the supersonic solar wind or the corona, the leading-order incompressible component of NI MHD "collapses in dimension", becoming essentially a superposition of 2D turbulence (orthogonal to the mean IMF) and a weak Alfven mode component. This theoretical result, coupled to numerous observational studies by others, has led now to a new paradigm for solar wind turbulence, *viz*., anisotropic turbulence comprised of a superposition of 2D turbulence and slab turbulence, with the power in the respective fluctuations approximately in the ratio of 80% to 20%. Observations appear to confirm not only the superposition model but the approximate ratio as well. Such a result is very different from our earlier ideas about turbulence in the solar wind which assumed either isotropic or slab descriptions of solar wind turbulence. This result now lies at the heart of almost all models of turbulence in the solar wind and solar corona.

A second area in which Dr. Zank's contributions to turbulence have proved of considerable significance is in the development of models that describe the transport of low-frequency turbulence in expanding and evolving flows such as the solar wind. Previous efforts described only the transport and evolution of linear wave modes – this is the so-called WKB model. Together with Bill Matthaeus, and Chuck Smith, Dr. Zank developed the description for fully developed turbulence that describes the radial and temporal evolution of the energy density in solar wind magnetic fluctuations. The theory exhibits very close agreement with Voyager and Pioneer observations to 80 AU. This work for the first time reconciled the turbulence perspective of the solar wind (dissipative heating, spectra, etc.) with the observed radial decay in fluctuation energy, presenting a completely new, tractable paradigm for the dynamical transport of MHD turbulence in the inhomogeneous solar wind. The most remarkable confirmation of the developed theory is found in a Physical Review Letters paper, where, by using turbulent dissipation to heat the solar wind, models of the radial evolution of the magnetic fluctuation energy density, temperature profile, and correlation length replicate their observed counterparts to 40 AU (the limit of accurate observations).

The combination of the NI MHD theory and the turbulence transport models has been a major development in our understanding of developed solar wind turbulence. Since low frequency MHD turbulence underpins the scattering of charged particles and the heating and driving of the solar wind throughout the heliosphere, the broader implications of this work are substantial. The superposition model of solar wind turbulence (2D plus slab) is now used to explain cosmic ray mean free paths, both the superposition model and the turbulence transport model are now used in modern cosmic ray modulation models, and related models have been used to explain the heating of the corona in open field regions and therefore the driving of the solar wind.

***Solar energetic particle events and Space Weather:*** Begun in 2000, Dr. Zank and colleagues developed the first physics based model that describes gradual solar energetic particle and energetic storm particle events. It had been thought that interplanetary shock waves were responsible for accelerating the solar wind ions that were commonly seen as large enhancements in the flux of energetic particles measured by spacecraft. However, no detailed model existed that described both the acceleration process and the subsequent transport of energetic particles after they escape the shock complex. The shock waves are typically driven by coronal mass ejections (CMEs). Dr. Zank developed a numerical model of the shock propagation and coupled this to a time-dependent particle acceleration model. The sophistication of this approach far exceeded anything done at the time and the subsequent models are rightly regarded as state-of-the-art. With Dr. Gang Li, a colleague at The University of Alabama in Huntsville, we have since extended this model by introducing a very sophisticated transport model based on a time-dependent implementation of a Monte-Carlo algorithm and modeling the wave-particle interaction using a quasi-linear approach for quasi-parallel shocks or a magnetic field line-wandering model for quasi-perpendicular shocks. This approach has made a considerable impact on the community because it can for the first time predict time intensity particle profiles, time-dependent particle spectra, particle anisotropies, etc. at 1 AU and throughout the heliosphere. The models include energetic heavy ions (Fe, O, etc.) as well as protons. With Dr. Zank's colleagues, they have investigated detailed models and compared them to observed events. The validity of this approach has proven spectacularly successful, and this is the only approach and model in the world that can accurately model for example the event integrated spectra of three SEP species (Fe, CNO, protons) simultaneously with no fitting. Dr. Zank emphasizes this because it is a remarkable tour-de-force to take a system as complex and stochastic as the region from the corona to beyond 1 AU and to independently and correctly account for the observed SEP event integrated spectra. The detailed match of observations and theoretically predicted event integrated spectra is astonishing, right down to bumps, wiggles, and roll-overs. Not surprisingly, this work represents one of the most promising approaches for Space Weather predictions of the particle radiation environment at 1 AU and beyond.