Happy New Year 2015 from SSX!

Here's a review of 2014 as well as plans for 2015. This has been a banner year for SSX in many respects. We've published (or at least had accepted) **seven** papers this year, including a nice PRL by David Schaffner. That's an all-time record for SSX. David, now a two-year SSX veteran, started out the year (actually end of 2013) with an excellent talk at AGU San Francisco that introduced our plasma wind tunnel results. We concluded the year with a well-received tutorial talk given by MB at the APS-DPP meeting in New Orleans. In between, we made a lot of trips in 2014 to promote the SSX plasma wind tunnel. It was my sabbatical year, so I was able to get away. We made visits to Iowa, Maryland, Villanova, Hamilton, Carleton, Santa Fe (for CMSO), David went to SHINE in Colorado, and we did the EPR meeting in Madison WI in August.

The other huge news of 2014 was that David and Erin had a baby girl (named Kiriah Dawn Schaffner), on Saturday Oct 11 at 12:39 pm (also David's birthday). She was 7 lbs 1 oz, and 21 inches. The "Kiriah" is Hebrew for "village." Kiriah joined mom and dad at Thanksgiving dinner at Casa Brown and was very well behaved (didn't eat much). Now at 3 months, she's already gotten big.

SSX now has a fancy website under the swarthmore.edu umbrella (http://www.swarthmore.edu/ssx-lab). This is also David's doing. It looks very professional and has the same layout as the rest of the Swarthmore website. I still operate my old one (http://plasma.physics.swarthmore.edu) but that will not be as up-to-date. The ssx-lab site has beautiful photos and some really professional-looking videos. One video was made here, another was done at Michigan during my 2013 visit there. On the subject of webpages, students Peter Weck and Adrian Wan were featured (along with me and David) on the "cover" of the main Swarthmore website. You can still find that piece (very well-written) by looking for "grappling with the unknown" on swarthmore.edu. Another nice piece is a podcast David did and appears on Physics Central called "solar winds and hot plasma experiments". Links to all these can be found on the ssx-lab site.

As you can see from pictures on the new website, we currently have the SSX plasma wind tunnel set up with a long extension. Recall that we now launch turbulent plumes up to 100 km/s with temperature well over 100,000 K ($T_i \cong 20\ eV, T_e \cong 10\ eV$). Our densities are running higher than in earlier SSX configurations ($n_e \geq 10^{15}\ cm^{-3}$ for most of the shot, with peak densities over $5 \times 10^{15}\ cm^{-3}$), magnetic field much higher ($0.5\ T$ when we run with double the capacitor bank), and our lifetimes shorter ($\leq 100\ \mu s$). In the current set up, the plasma plume emerges from the extension into an expansion volume (the original SSX chamber), where we have a fast camera set up. Images from the Xybion camera will appear in a JPP paper (see below) but you can also see some images on the new website.

I'd say the scientific highlight of 2014 was David's *Physical Review Letter* entitled "Observation of turbulent intermittency scaling with magnetic helicity in an MHD plasma wind-tunnel". In the paper, David studies objects called increments of the magnetic field, e.g. $\langle \mathbf{b}(\mathbf{t}) - \mathbf{b}(\mathbf{t}+\tau) \rangle$, and showed that a probability distribution function PDF of increments from the SSX plasma wind tunnel had "fat tails". This hadn't been observed in a laboratory plasma, but had been observed in the solar wind. The idea is that magnetic structures that naturally arise in the turbulence give rise to statistically large increments in a time series.

We've done a review paper and a tutorial paper (see below and on the website). The tutorial paper will appear in Physics of Plasmas and is the companion piece to the tutorial I did at the APS-DPP meeting in New Orleans in October. The PoP paper is the first one we've done using solar wind data (from the WIND spacecraft). This marks another milestone for us. Beginning with the AGU meeting late in 2013, and including David's participation in SHINE (see below), we are now in the solar wind observation business with access to incredible data from state-of-the-art spacecraft (like WIND and Cluster). This entree into satellite data was provided by new collaborator Robert Wicks, so thanks to Robert for that.

CMSO: Disappointing news is that our renewal for the NSF Center for Magnetic Self Organization (CMSO) was denied. SSX has been part of CMSO since it's inception ten years ago. 2015 will be the final year of CMSO. We had spent a lot of time in 2014 putting together the renewal proposal (back in Jan 2014). We were selected as finalists, and had a site visit at NSF headquarters May 12-13. We got the disappointing news at the end of May. During the site visit, we learned that all the other finalist groups for NSF Centers were in the same hotel. We were the only plasma physics Center in the competition, but we recognized physicists from around the country. At one point, due to a mix-up in scheduling, another Center group appeared in the NSF waiting room before our presentation. I recognized Nobel prize winner Bill Phillips from NIST, so I knew the competition would be stiff. We also tried for a 2014 Kaufman Foundation grant with Penn State astrophysicist Derek Fox but that didn't fly either. Our next new grant application will be with ARPA-E (with a new collaborator Simon Woodruff).

Undergraduate colloquia: MB had the opportunity to do several undergraduate colloquia in 2014. One was at Carleton College, where my daughter is now a sophomore. It was great to have Violet (and her friends) in the audience. I also had a good visit to Hamilton College in upstate NY where Swat alum (and former visiting prof) Seth Major works. I test drove the turbulence tutorial at both places, as well as at a colloquium here at Swarthmore in September. I gave a more fusion-y talk at Villanova in March 2014 as part of the AAPT workshop there.

Technical talks: We made visits to both Maryland and Iowa early in 2014 (Jan and Feb). Both places have very strong space and solar wind

physics groups. We visited with Jason TenBarge, Rob Wicks, as well as Matt L at Maryland, and had a good visit with Greg Howes and Kris Klein at Iowa. David gave the Maryland talk and we both gave talks at Iowa (mine was a colloquium). David also gave an excellent talk at likely the last CMSO group workshop in Santa Fe, NM in May. There we had a good discussion with Joe Borovsky about some of the stuff we see in the SSX plasma wind tunnel. The Exploratory Plasma Research EPR meeting was in Madison, WI Aug 5-8, 2014. I was the conference organizer and I'm chair of the EPR group. This is a fusion meeting of non-tokamak ideas and schemes. There were a few other experiments in the high velocity merging category. David gave the talk, and we met with folks from ARPA-E (Advanced Research Projects Administration for Energy).

SHINE: David went to a meeting in Telluride CO called SHINE June 21-28. It's really a meeting of experts. David gave an informal presentation on laboratory comparisons to space plasma observations. David made important connections with the solar wind community there including with Chris Chen (Imperial College) who is helping us with Cluster data. Virtually the whole solar wind community was there.

APS-DPP: Our big trip (as it is each year) was the APS-DPP meeting, this time in New Orleans Oct. 27-31, 2014. Peter Weck, David, and I attended the meeting. Peter's poster abstract is below. We had a nice celebratory dinner at a place called SoBou. I gave a review talk on Wednesday afternoon called "MHD turbulence: observation and experiment." It seemed pretty well attended (I estimated that maybe 150 people were there). There's always something of an SSX/Swarthmore reunion at APS. We saw Ken F, Matt L, Vernon, Slava, Cameron, and Mike Rosenberg. Matt gave a nice invited talk on Monday morning about Fokker-Planck calculations he's done at Maryland. Lots of folks visited Peter's poster on Tuesday. Thanks to everyone that dropped by. Thanks also to everyone that came to my tutorial talk.

Summary of 2014:

We started 2014 working on the original short $L = 0.86\ m, D = 0.17\ m$, L:R = 10:1 thick-wall flux conserver, then switched during the summer of 2014 to the extension, with a 1.7 m long flux conserver that emerges into the original chamber (now called the expansion chamber). We ran with just one linear probe (Ken's) and the Mach probe (Alex Z's) in the shorter configuration; magnetic probe and double Langmuir probe (Darren W's) in the longer configuration. Most of the data in the papers below are from the shorter version, but notably, we have some fast Xybion photos as the plasma emerges from the extension into the expansion volume.

Here's a summary of the methods we've been employing. Have a look at the tutorial/reviews for more details. (1) We've been studying correlations (both in space and time) by multiplying a signal (usually magnetic) by a copy at a different time, or different position. This tells us how long it takes for the turbulence to "lose its memory". (2) The frequency content

of the signal (how much high or low frequency activity) is revealed by the frequency power spectrum (either Fourier transform or Wavelet). (3) If the signal is perfectly random, then we expect (after some delay) there to be as many upward fluctuations as downward, and there to be very few large excursions. We can study a histogram of the "increments" and we find that SSX has a preponderance of large changes associated magnetic parcels and coherent structures. (4) Structure functions are higher order moments of these increments. (5) Finally, we've been studying the order magnetic field values appear in a time series. If all ordinal patterns of say 5 sequential points appear with equal likelihood, then the time series has maximal permutation entropy, H. This would be all five in ascending order, and all in descending order, and all 120 combinations in between. We find SSX turbulence and the solar wind both have high permutation entropy (solar wind is higher).

Increments, Spectra, and Entropy (David/Peter): The core science projects from 2014 were turbulence analysis of data from the SSX wind tunnel. The tools we used are described above and in the PoP tutorial and PSST review. A key physics result was David's observation of "fat tails" in the PDF of magnetic increments mentioned above. It turns out that the fattest tails (highest kurtosis) come from discharges with more helicity. David also published a nice paper on variance anisotropy in our turbulent spectra in ApJ. Peter and David just had their paper on permutation entropy accepted in PRE. Peter's CH plane diagram appears on the latest SSX tee shirt (we had a big tie-dye party at Casa Brown in July).

Xybion camera: During the summer of 2014, we finally took our first images of SSX plasma with a Xybion 750 fast framing camera on extended loan from PPPL. It is capable of taking a single frame at 20 ns shutter speed. Our plasmas move up to 10 cm per μs so the Xybion freezes the motion pretty well ($\leq 2\ mm$ of blurring). We have a large window and the Xybion has a view into the expansion chamber from above. Steve built a nice moveable mount for the camera. We had some issues with the camera (a board inside fried) but with the help of Paul Jacobs and a little repair company in San Diego, we got it running again. Some images from the Xybion appear on our website and the JPP paper noted below.

Papers and manuscripts (2014): Seven publications in 2014, though some have yet to appear. The latest one, a tutorial based on the APS-DPP talk I gave, was just accepted and should appear in the annual May issue of Physics of Plasmas dedicated to the prior DPP meeting. It was submitted in Dec 2014. These are all on the new ssx-lab website.

1. M. R. Brown, D. A. Schaffner, and P. J. Weck, "Magnetohydrodynamic Turbulence: Observation and Experiment", *Physics of Plasmas* (to appear May 2015).

2. P. Weck, D. A. Schaffner, R. Wicks, and M. R. Brown, "Permutation

Entropy and Statistical Complexity Analysis of Turbulence in Laboratory Plasmas and the Solar Wind", *Phys. Rev. E* (to appear 2015).

3. M. R. Brown and D. A. Schaffner, "SSX MHD plasma wind tunnel", *J. Plasma Physics* (to appear 2015).

4. M. R. Brown and D. A. Schaffner, "Laboratory sources of turbulent plasma: a unique MHD plasma wind tunnel", *Plasma Sources Science and Technology*, invited review, **23**, 063001 (2014).

5. D. A. Schaffner, M. R. Brown, and V. S. Lukin, "Temporal and Spatial Turbulent Spectra of MHD Plasma and an Observation of Variance Anisotropy". *Astrophysical Journal* **790**, 126 (2014).

6. D. Schaffner, A. Wan, and M. R. Brown, "Observation of turbulent intermittency scaling with magnetic helicity in an MHD plasma wind-tunnel", *Phys. Rev. Letters* **112**, 165001 (2014).

7. D. Schaffner, A. Wan, V. S. Lukin, and M. R. Brown, "Turbulence analysis of an experimental flux rope plasma", *Plasma Physics and Controlled Fusion* **56**, 064003 (2014).

Students: We had two excellent students during summer 2014 (Peter Weck '15 and Emily Hudson '17). The total number of SSX alums is approaching 50. Peter is writing a senior thesis as part of the honors program here at Swarthmore College. This will be the first SSX thesis since Vernon Chaplin '07. I've read the first draft and it looks very good. Peter came to New Orleans for the APS meeting and presented a poster.

P. J. Weck, E. R. Hudson, D. A. Schaffner, R.T. Wicks, M. Brown, V. Lukin

Permutation entropy analysis of dynamical turbulence in the SSX MHD wind tunnel and the solar wind. The statistical character of turbulence in the plasma wind-tunnel configuration at the Swarthmore Spheromak Experiment (SSX) and the solar wind is evaluated using ordinal pattern-based measures of complexity. The SSX MHD wind tunnel measures fluctuations in magnetic field, velocity, and density as highly magnetized spheromaks (typical values are $B \approx 0.1$ T, $n \geq 10^{20}$ m^{-3}, and $T \geq 20$ eV) evolve dynamically into a relaxed state. Flow speeds are measured with a visible light array. $\dot{B}$ time series for 3 spatial directions recorded by a 16-channel, high-resolution probe array embedded in the chamber are analyzed using the permutation entropy, H, and Jensen-Shannon statistical complexity, C_{JS}. By calculating the position of signals on a complexity-entropy plane as in [1], the degree of stochastic, periodic, or chaotic dynamics can be evaluated. Complexity-entropy positions of SSX signals are compared to those of turbulent fluctuations in the solar wind and the Large Plasma Device (LAPD) as well as Hall-MHD simulations of the SSX plasma, and it is found that the dynamics in the SSX plasma source are more truly turbulent than those in the LAPD but less stochastic than fluctuations in the solar wind. [1] Rosso, et al. *Phys. Rev. Lett.* **99**, 154102 (2007).

Emily Hudson '17 worked with a new $H\alpha$ detector array for SSX (originally built by Jeffrey) to measure plasma plume velocities by time-of-flight. She did an excellent job, and for the first time, we have good statistical data of plasma velocities in the SSX wind tunnel for hundreds of shots. The results are histograms of mean velocities, so we can see under what conditions we get the highest velocities. She found that for certain helicity settings, we can attain a mean velocity of about 75 km/s.

Plans for 2015:

- **Full 2.5 m SSX wind tunnel (early 2015):** We are now beginning to prepare SSX for operation of the full 2.5 m plasma wind tunnel. This means that a $D = 0.17$ m flux conserver will run the entire length of the device from the extension through the main chamber. Slava has moved to NSF (congrats Slava!), so his simulation time on HiFi will be limited.

- **Papers (David/Peter/Rob W):** There are several papers in the works. Two are very close to submission. One is about temporal structure functions of magnetic field in SSX in the inertial and dissipation range (David, ApJ), the other is about spatial correlation functions in SSX (work originally done by Adrian Wan '15). David is also working on a paper on the distribution of angular increments in SSX. With the help of Rob Wicks and Chris Chen, we now have access to high-temporal cadence magnetic data from the solar wind. We published our first solar wind analysis in Physics of Plasmas using WIND data (to appear May 2015), but we are now beginning to study very high resolution data from the four-spacecraft armada called Cluster (0.04 second step size). David and Peter plan to perform more complexity and entropy analysis on that dataset, looking for changes in complexity with scale. For sure, this will appear in Peter's thesis (due in March), but I think there's enough material for another CH paper. Rob will visit Swarthmore for a colloquium in Feb.

- **ARPA-E:** Occupying our time at the moment is a proposal to ARPA-E. The idea here is to fund the development of a plasma accelerator module for the extension. We hope to push our flow speed up to over 100 km/s and higher Mach numbers. We hope to collaborate with Simon Woodruff on this. HiFi simulation support will come from students at Wisconsin (Emily Lichko through the PSI-Center and Carl Sovinec).

- **Meetings:** The APS-DPP meeting is in Savannah, GA Nov 16-20, 2015. MB is slated to give a talk at U. Maryland (mostly on careers in liberal arts colleges) on March 10, 2015. David is visiting Bryn Mawr in Jan and WVU in Apr. We're hoping to schedule a visit to New Hampshire (UNH) to visit Kris Klein and Chuck Smith (another big solar wind group). The IPELS meeting is slated for August 2015 in Scotland.

cheers and happy new year for 2015, mb