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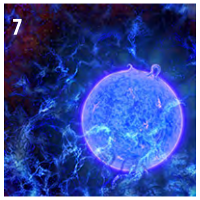

Astronomy in the News

IAN O'NEILL

A rundown of some of the most exciting developments in space and time.

Opportunity Sleeps

TRACY STAEDTER

As an unprecedented dust storm blankets the Martian atmosphere in darkness, the 14-year-old rover goes silent.

Billions of Black Holes

MATTHEW R. FRANCIS

Many undiscovered black holes likely lurk throughout the Milky Way—this is how we might find some of them.

Chasing Shadows

STEVE MURRAY

Two teams of scientists studied the 2017 solar eclipse from high-flying aircraft. A year later, results are starting to come out.

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on the cover

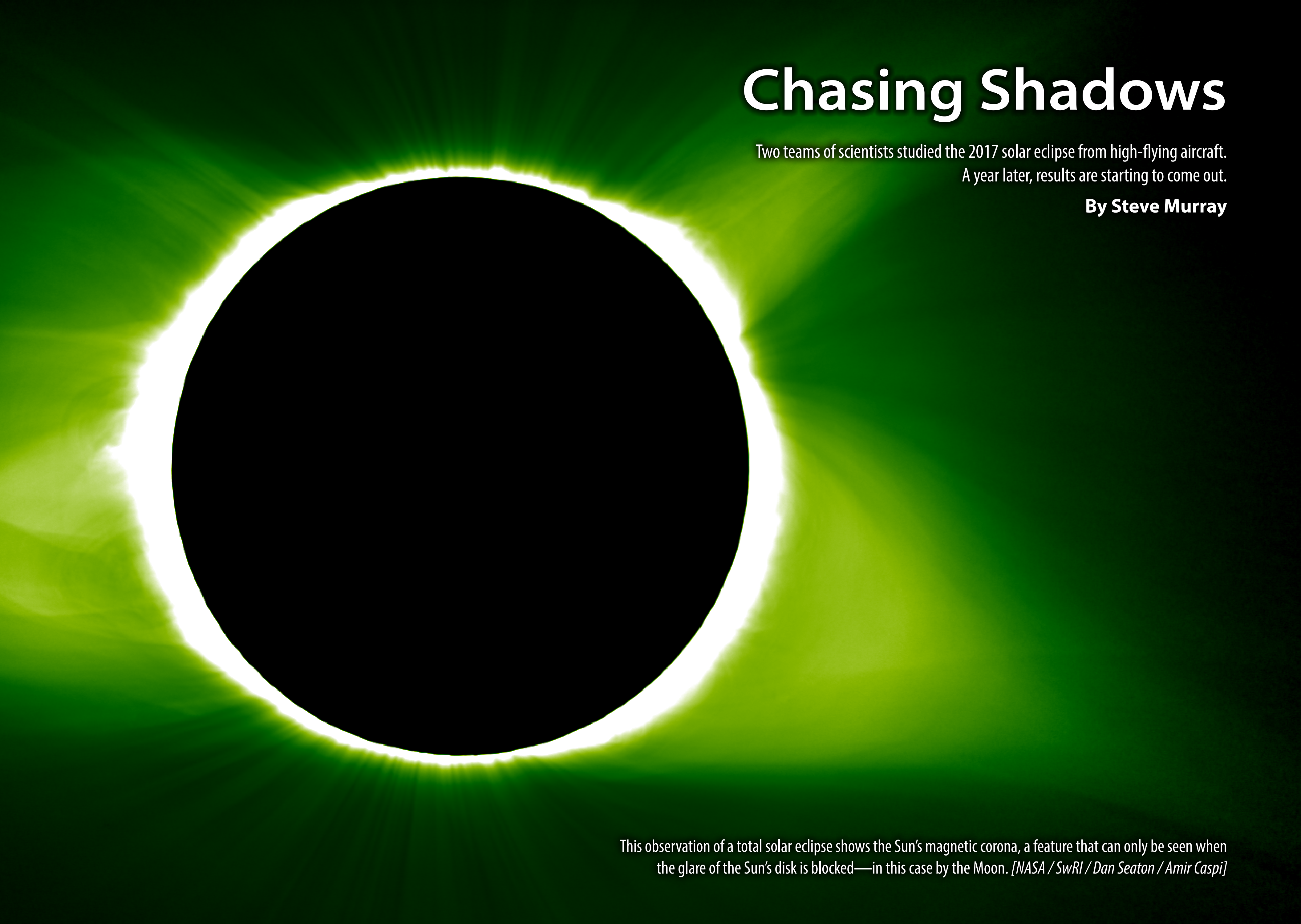
Front: In an effort to seek out our Sun's siblings throughout our galaxy, the Galactic Archaeology survey (GALAH) is studying the spectroscopic signature of other stars. Shown here is a spectroscopic observation of our Sun. The black bands in the spectrum represent different abundances of chemicals in the solar atmosphere that can be viewed as a stellar DNA sequence. *Credit: N.A. Sharp, NOAO/NSO/Kitt Peak FTS/AURA/NSF.*

Back: A team using the incredible ultraviolet imaging capabilities of Hubble have created the most comprehensive high-resolution ultraviolet-light survey of star-forming galaxies in the local universe. The catalogue contains about 8000 clusters and 39 million hot blue stars. Shown here is the stunning spiral galaxy NGC 6744, about 30 million light-years away. *Credit: NASA, ESA, and the LEGUS team.*

Chasing Shadows

Two teams of scientists studied the 2017 solar eclipse from high-flying aircraft. A year later, results are starting to come out.

By Steve Murray



This observation of a total solar eclipse shows the Sun's magnetic corona, a feature that can only be seen when the glare of the Sun's disk is blocked—in this case by the Moon. *[NASA / SwRI / Dan Seaton / Amir Caspi]*

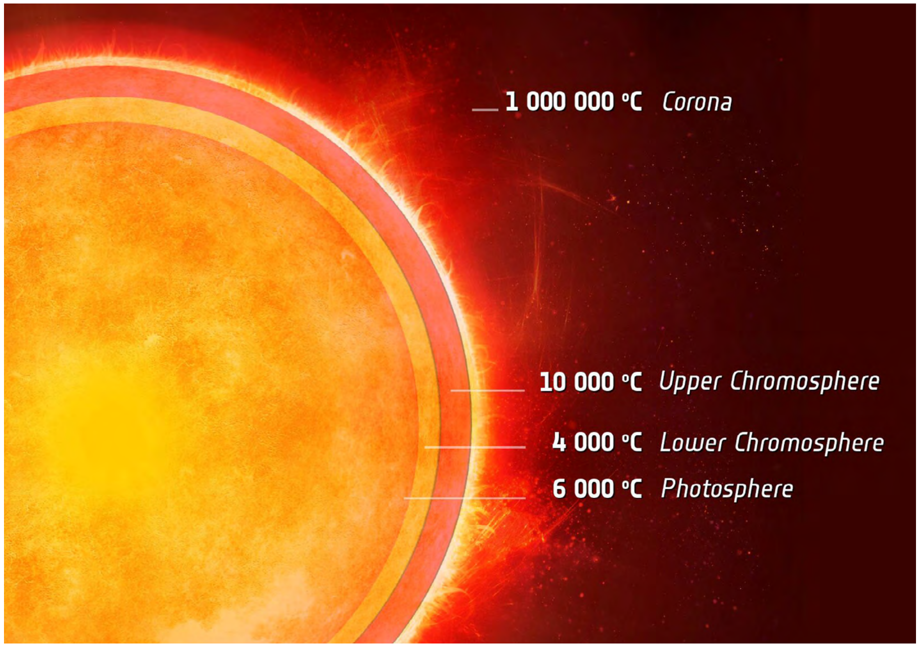
While millions of people observed the Great American Eclipse of 2017 from places all around the country, two science teams observed the event from high above it. Researchers flew instrument-packed aircraft above 90 percent of the Earth's atmosphere in an effort to gain new insights into the mechanisms that drive the temperature and structure of the Sun's corona. One year later, scientists are showing what they've learned so far from their data, and discussing what they still expect to find.

Coronal Questions

The corona makes up the outermost layer of the Sun's atmosphere. Its characteristic crown-like shapes result from the interaction of hot plasma with strong magnetic fields. Because the corona is 10 million times less dense than the chromosphere beneath it, however, it can only be seen with a coronagraph or during a total solar eclipse—it's usually drowned out by the glare of the Sun's disk.

Astronomers are still trying to explain how temperatures increase so dramatically—from around 5,500 degrees Celsius at the chromosphere to several million degrees Celsius in the corona, a puzzle known as the "coronal heating problem"—and how it manages to appear so ordered. "We know energy is getting into the corona to heat it, but we don't know how that energy gets there," says Amir Caspi, Senior Research Scientist at the Southwest Research Institute (SwRI) in Boulder, Colorado. "We also don't understand why the corona is so well-structured. It should be a tangled mess, but the corona somehow keeps itself organized."

Some of the best opportunities for examining these properties are provided by total solar eclipses, hence the rush of scientific observing projects surrounding the 2017 event. "Coronagraphs aren't as good as a direct eclipse," says Phil Judge, Senior Scientist in the High Altitude Observatory at the National Center for Atmospheric



The atmosphere of the Sun consists of a lower photosphere and, just above it, the chromosphere. Above the chromosphere, solar plasma experiences a dramatic temperature increase in the corona. *[Public Domain/Wikimedia Commons]*

Research (NCAR). "It's not just because of diffraction effects, it's because of all the scattered light coming in to the coronagraph from the atmosphere above. Although space-based coronagraphs are largely free of the problem, they still have residual diffraction." The Moon is a much better occulting disk because it's so far away that there is virtually no diffraction around the edges.

Both science teams saw airborne astronomy as a promising path to clearer measurements. While the corona radiates energy across a wide spectrum, short wavelengths such as X-rays don't penetrate the Earth's atmosphere. Lower wavelengths, including visible light and infrared, could provide more accessible insight into coronal behavior. "While you could do visible light observing from the ground," says Caspi, "you have to look through all that atmosphere, which is going to distort your image. Furthermore, emission and absorption of the atmosphere contaminates the three to five micron infrared band that both flight teams were trying to observe."

"The Sun has never been properly surveyed in the infrared," says Judge, "so the August eclipse offered us an opportunity to observe something entirely new. Infrared is one of the best places to go to measure the magnetic field of the Sun."

Airborne observations were also seen as a way to extend the available opportunity for collecting data. The totality of an average eclipse lasts only two to three minutes, an extremely short interval for measuring coronal dynamics. "Being on an airplane meant that we could put ourselves exactly where we needed to be," says Caspi, "and chasing the eclipse meant that we could get extra time, especially by using two airplanes. Space-based platforms can't position themselves in the exact path you might want, like an aircraft, and don't have the telemetry performance; there's a limit to how much data you can send down from a spacecraft."

One of the WB-57F jets is readied for a test run at Ellington Field in Houston. The instruments are mounted under the silver casing on the nose of the plane and removed before flight. *[NASA's Johnson Space Center/Norah Moran]*

Assembling the Tools

Phil Judge and his colleagues used the NSF/NCAR Gulfstream-V High-performance Instrumented Airborne Platform for Environmental Research (GV HIAPER) aircraft for the flight portion of their project. "I made a general announcement to the astronomy community that we had this NCAR aircraft," says Judge. "Ed DeLuca of the Harvard-Smithsonian Center for Astrophysics (CfA), jumped on the opportunity and came with an imaging spectrometer." The Airborne Infrared Spectrometer (AIR-Spec) was carried aloft to measure 5 magnetically sensitive coronal emission lines, a first for high resolution coronal imaging spectroscopy from the upper atmosphere.

The team augmented its airborne data measurements with a set of ground-based instruments that included a forward-looking infrared (FLIR) camera, an imaging polarimeter (POLCAM), and an infrared Fourier Transform Spectrometer (IRFTS). "I actually tried very hard to get the IRFTS onto the aircraft," says Judge, "but we didn't get the funding we needed."

The eclipse marked the astronomy debut of two NASA WB-57 aircraft in support of the SwRI project. They are the oldest aircraft in the NASA fleet and the only three flyable models in the world. "We've been looking at flying the WB-57s for astronomy for a number of years, says Caspi, Principal Investigator of the NASA WB-57 mission. "The eclipse is what finally got it to click."

The SwRI project was an exercise in repurposed technology. Each WB-57 was equipped with an AIRS/DyNAMITE (Airborne Imaging and Reconnaissance System/Day-Night Airborne Motion Imagery for

Three WB-57F jets fly in formation over Houston, Texas. *[NASA/Southern Research]*

Terrestrial Environments) system in its nose. Designed and built by Southern Research, each system combined a gyro-stabilized high-definition television camera and FLIR camera. The packages were originally designed for tracking Space Shuttle launches, however, and not for astronomy research, so Southern Research incorporated several upgrades to make the systems suitable for recording the eclipse. "We didn't have a lot of time or money to develop our own instrumentation," says Caspi, "so we adapted existing instruments. AIRS/DyNAMITE already had visible light and infrared capability so it was perfect for our needs. Southern Research contributed time and resources far beyond our expectations. They became major partners and were critical to our success."

The Gulfstream V chased the eclipse across Missouri, Illinois, Kentucky, and Tennessee at an altitude of over 14 kilometers (47,000 feet), and obtained measurements during about four minutes of totality. Jenna Samra, a Harvard PhD student who designed the inertial stabilization platform that guided the AIR-Spec system, also flew aboard the aircraft to supervise data collection and equipment operation during the eclipse. The skies were crowded for the event. "Controllers told us to land immediately after our mission," says Judge, "because of all the other eclipse chasing aircraft in the sky that day."

Both WB-57s flew at about 15 kilometers (50,000 feet) along the path of totality. The planes were staged about 100 kilometers (62 miles) apart while following the eclipse track, which meant that both aircraft were simultaneously in the Moon's shadow for about 10 to 15 seconds. And, while each WB-57 experienced about four minutes of totality, the science team expects to obtain over seven and a half minutes of continuous totality once the data are combined.

Each NASA aircraft carried a pilot and a sensor equipment operator (SEO) responsible for managing the AIRS/DyNAMITE system. One of the systems added some excitement to the mission. "My hair was absolutely on fire from the first part of the mission," says Don Darrow, an SEO with Southern Research. "My system didn't work properly and one of my displays wasn't available, so I had to collect data and troubleshoot at the same time. Fortunately, everything got resolved just before the eclipse and the AIRS system operated by Cary Klemm, the other SEO, was just fine."

All of the data was recorded onto hard drives in each airplane and downloaded after they landed.

Looking at the Data

Although all system calibration and data validation tasks aren't yet completed, both teams have reported their initial results.

The AIR-Spec instrument used aboard the Gulfstream V was a slit spectrometer, which measured discrete locations around the Sun. "We achieved four positions during the flight," says Judge, "and the spectrum is somewhat different at each one. This is very important to know, of course, as the signature of the Sun is determined by the structure underlying it. We see different things because that structure is different.

"I'm very much interested in solar magnetism because that's where all the energy is," he adds. "What we see in the corona is the result of the dissipation of that energy, not the cause of it. The thermal structure is also very well organized, but a lot of research only looks at thermal organization and not the magnetic field; and they don't really ask questions about it." Judge had predicted in 1998 that the five wavelengths successfully measured by AIR-Spec should be visible in the corona. One of the lines, for magnesium, had never been seen before.

"This is the first time we've obtained results like these for high

This photograph shows Southern Research Sensor Equipment Operator Donald Darrow in a WB-57 during an eclipse flight. *[Donald Darrow]*

resolution coronal imaging spectroscopy," he says, "and it opens a new infrared window on the solar corona. It could be a pathfinder method for future observations of coronal magnetic fields."

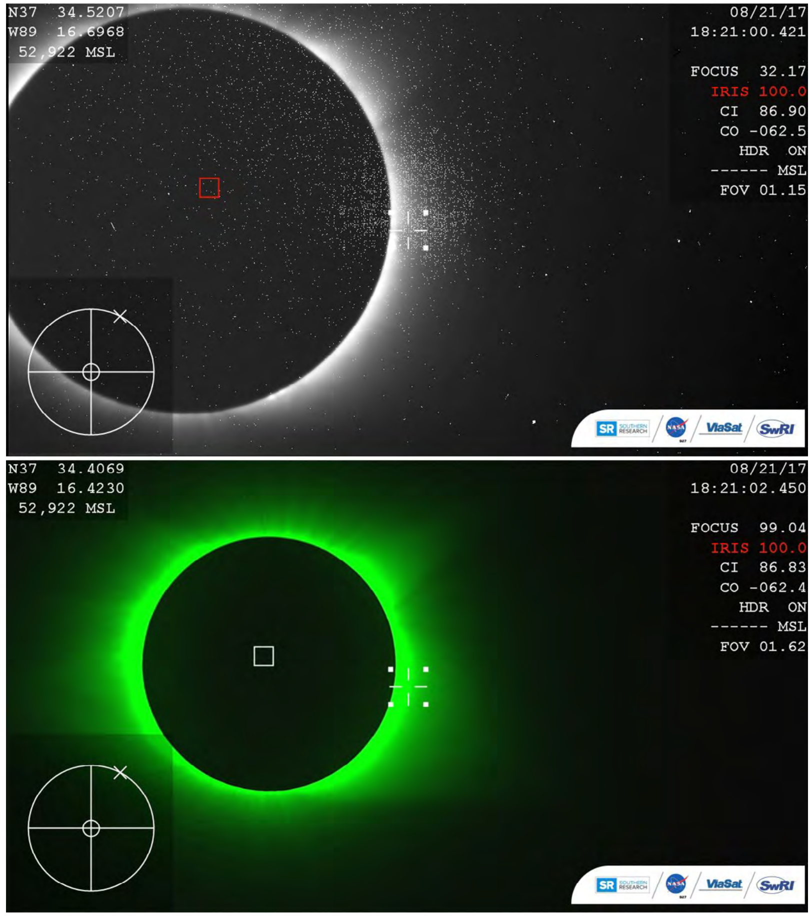
The SwRI team focused on the "green line" with its visible light measurements. "The green emission from Iron 14 (Fe XIV) helps us isolate the magnetic structures in the corona filled with hot plasma," says Caspi, "from the background of photospheric light scattered by the corona. This helps us to better see the coronal structures and to try and understand how they stay so well organized. The big loops you see in the corona are rooted in the photosphere below. The photosphere looks kind of like a pot of boiling water, with convective cells bubbling up and also causing twisting and turning at the surface. This surface convection should twist and tangle the loops, but it doesn't—that's what we're trying to figure out."

The team had to process the data to remove jitter from aircraft motion, and to co-align the images by stacking them on top of each other. "You can immediately see more structure and striations in the calibrated images" says Caspi. "What we're looking for are ripples and waves."

Alfvén waves are magnetic ripples that flow through the corona. "The magnetic structures that we see in the corona are rooted in this roiling mass, says Caspi, "and you'd think it would tangle them up, but it turns out that they don't; they stay very well structured even though they're constantly twisting and turning. That means that the magnetic field is reconfiguring itself to constantly release little bits of twists and tangles to stay combed. Although we don't really know, we conjecture that it's a magnetic reconnection phenomenon—when closely spaced but oppositely oriented magnetic field lines 'annihilate' and cause the field to reconfigure."

These same waves, or waves related to them, may also be getting dissipated in the corona and releasing energy as heat, so the process they're looking for to explain the stability of the corona's structure could also be responsible for its heat. Although possible wave motion could have been captured in the SwRI data, the team can't yet rule out that the data processing required to remove image jitter might, itself, be a cause of that motion.

The infrared data collected by the SwRI team may turn out to be the most surprising. "The infrared was kind of a bonus for us,"



Both stabilized telescopes aboard the WB-57F aircraft successfully acquired science data and images during the August 21 eclipse, including observations of the solar corona during eclipse totality and of Mercury during the eclipse partial phase. *[NASA]*

says Caspi, "because the camera was already on the airplane. We captured one of the very first images of the corona at infrared wavelengths. It's intriguing because it's in the three to five micron range which is basically inaccessible from the ground. The atmosphere absorbs and emits really strongly in that band.

"The infrared data is quite tantalizing," says Caspi, "so the 'bonus' science that we set out to do—that wasn't really driving our project—might turn out to be very interesting. We're still working on the analysis, but these brand new observations could yield some really exciting results."

Summaries of these results have been presented in public forums and at least one paper has been released. The two teams are now discussing a collaboration for the next phase of their analysis. "I think the possibility of there being an interesting overlap between us is still there," says Judge. "And it's research—you don't know what you're going to get. If you did, it wouldn't be research."

"The experiment that Jenna and Phil were working on included an airborne spectrometer," says Caspi, "and they were looking in similar wavelengths to ours. Their instrument was a slit spectrometer and looked along a narrow slice of the Sun whereas we were observing the full Sun in infrared. We have a lot of good spatial information while they have a lot of good spectral information. So by combining our data we can hopefully learn even more about what the Sun is doing in these near-infrared wavelengths."

What's Next?

While there is more information to mine from these mission results, the issues will likely not be resolved from these flights alone. "I think there are much more fundamental questions that we need to answer to understand the relationship between energy going up and then dissipating in the corona and why it has to organize itself in the way that it does," says Judge. Nevertheless, several important advances have already emerged from this work that will advance both solar physics and airborne astronomy in general. "Some of the technical issues we've sorted out in our ground-based and flight instruments will be particularly relevant to the Daniel K. Inoue Solar Telescope (DKIST)," says Judge. "The 4-meter instrument is being built on Haleakala, Maui and, with an infrared coronagraph, it will be able to observe the Sun in exquisite detail. The work we've done leads toward a better understanding of the challenges, so we can hit the ground running when DKIST begins operating in 2020."

This artist's rendering shows two WB-57 during an eclipse flight. *[NASA/Faroe Islands/SwRI]*

"One of the SwRI engineering goals was to see whether the WB-57 would make a viable platform for airborne astronomy. "And it really does," says Caspi. "I think one of its greatest strengths would be accessibility for daytime targets. There ARE celestial targets that are up during the day and those generally aren't accessible to nighttime observatories. We're hoping it's the first of many times the WB-57s will be used for astronomy."

The Gulfstream V has already been requested to support the 2019 eclipse in South America, although the project will have to compete with other demands for its time. "There's still a need to get the IRFTS aboard an aircraft, too," says Judge. "Maybe that will happen during the next eclipse cycles."

The SwRI team is also looking to get the WB-57s to South America in 2019 and 2020, ideally with some equipment upgrades. Additional flights would allow the astronomers to compare observations across an interesting shift in solar activity. The 2017 eclipse occurred a few years after solar maximum but a few years before the solar minimum of 2019 and 2020, when the corona should appear more symmetric. "Because the Moon will be closer in 2019," says Caspi, "we might actually get up to 12 or 13 minutes of totality, between the two aircraft. I'm hoping it's the beginning of many more interesting missions!" ✪

STEVE MURRAY is a freelance science writer and NASA Solar System Ambassador. A former research engineer, he follows developments in astronomy, space science, and aviation.