SKY & TELESCOPE

PARALLEL IMAGING by Richard S. Wright, Jr.

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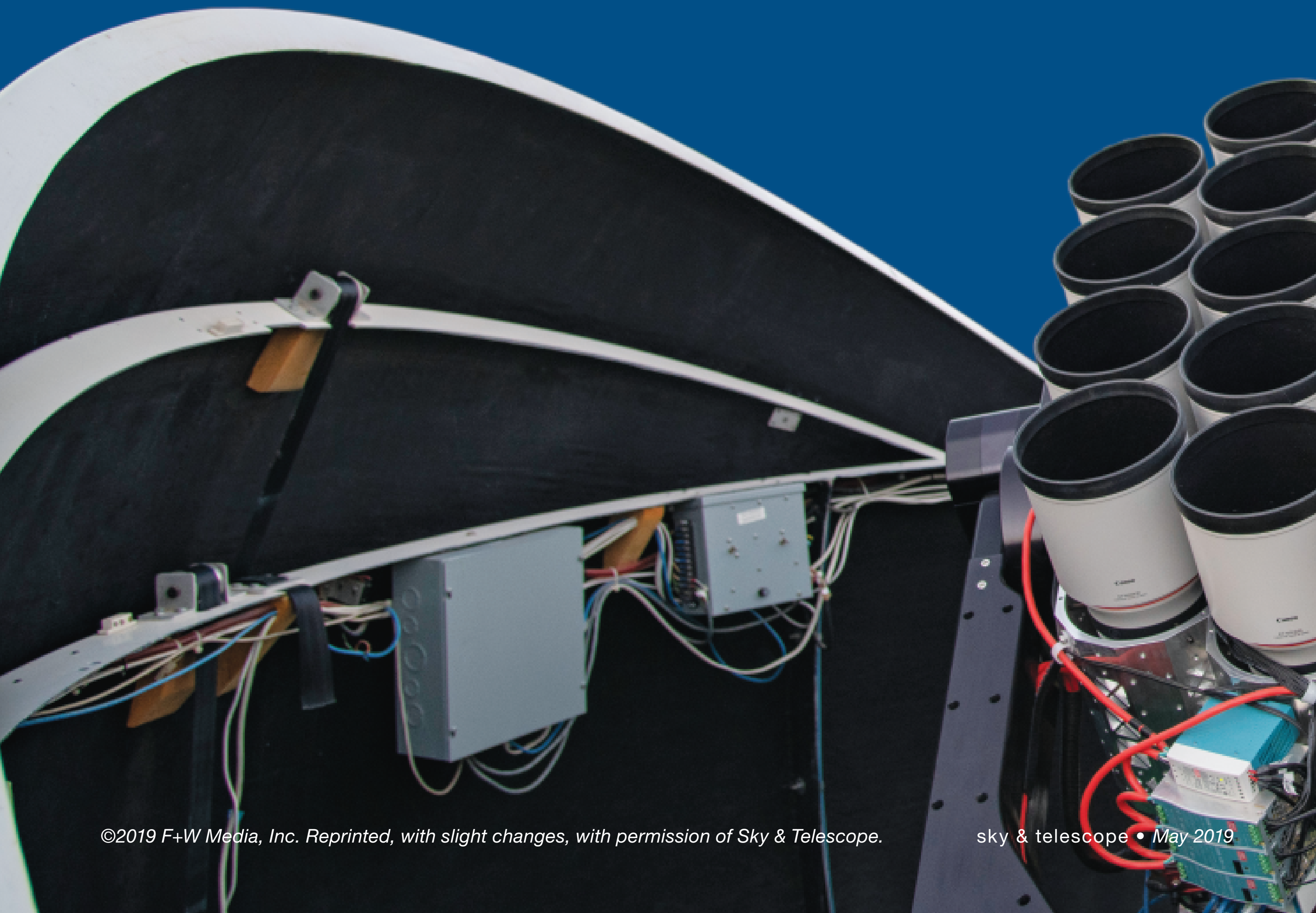
S&T Article

Insect Eyes on the Deep Sky

A team of astronomers uses an innovative approach to create the world's fastest telescope system.

They say two heads are better than one. When it comes to astronomy, it's also true that two *optics* are better than one. As an amateur astrophotographer, I find it exhilarating to have two mounts running simultaneously, taking exposures of the same target. It's like getting two nights for the price of one! The first time I tried such a thing, I jokingly called it parallel processing. As a career software developer, the idea of using multiple CPUs to speed up a computational task is as obviously beneficial as having multiple painters working on your house at the same time. You get nearly a linear performance gain for every processing unit you can throw at it.

The same goes for professional astronomy. There are some areas of research where a parallel approach to imaging might be profitable, perhaps even to the point of leapfrogging what the world's largest instruments can do. One such application came up serendipitously in a discussion between two friends having dinner at a Toronto restaurant.



Those friends were Roberto Abraham of the University of Toronto, and Yale University's Pieter van Dokkum. Both were frustrated with the fact that most research projects have a budget and lifespan that far exceed the typical graduate student's tenure. It seemed nearly impossible to engage a graduate student on the new construction of an instrument through its completion, much less for him or her to use it to gather data. It would be great if it were possible to build an entry-level, cutting-edge system that didn't cost a minimum of $10 million or take ten years to finish.

Both professors were trying to detect extremely low surface brightness features around galaxies. Current models predict that most galaxies should be surrounded by debris from their formation, observable as large swaths of stars in faint glowing halos. These halos are hard to detect, however. They are also thought to be quite large and extended, requiring wide-field instruments with fast focal ratios. But backscattered light commonly plagues fast optics and large mirrors, which creates even more challenges for detecting the very faintest of signals necessary for this kind of observational confirmation.

Then one professor had a crazy idea. For extended objects, all that's needed is a fast focal ratio on an optic with very low light-scattering characteristics. Van Dokkum, who is also an avid wildlife photographer, learned that Canon had just introduced a revolutionary new nano-coating technology with a subwavelength structure that the manufacturer claimed had unprecedentedly low-light-scatter characteristics. His idea was to put a commercial CCD camera behind one of these new lenses and shoot some galaxies to see if the camera picked anything up around it. Abraham didn't think it would work due to all the additional lens elements in a high-end telephoto lens, but van Dokkum was confident that Canon's new nano coatings might do the trick, so they agreed to give it a try.

CROWDED GAZE
Seen at left and above, **Dragonfly 1** stands ready for an evening of observing. Each of its 24 specially coated Canon 400mm f/2.8 lenses is mated with its own SBIG STF-8300M CCD camera. All 24 are aligned to image the same target simultaneously. Unless otherwise noted, all photos were provided by the Dragonfly team.

DENNIS DI CICCO (2)

The two acquired one of the Canon lenses and borrowed a slew of amateur equipment, including a tracking mount, a CCD camera and autoguider, and a commercial lens adapter. Without telling colleagues of their plan, they drove out to an observatory in Quebec. Their first target was M51, and after some modest integration time with the Canon 400mm f/2.8 lens, they found that it easily brought out the known stellar plumes around M51 and its companion, NGC 5195.

▲ **TRIPLED GAZE** Roberto Abraham mounts an autoguider camera on the proof-of-concept three-lens prototype.

A Dragonfly Is Born

With the proof-of-concept testing a success, the team decided to acquire three lenses and cameras, in order to accumulate more data simultaneously and get a stronger signal during each outing. The plan was to wait until there was a weather break and simply run out and get some data. However, every seasoned amateur knows what happens to the weather when you buy new gear. After several weeks without a clear night or with conflicting schedules, the team reevaluated its approach. The project really required a permanent home under better skies. It was then that they contacted Mike Rice, proprietor of New Mexico Skies (**newmexicoskies.com**), a remote telescope hosting facility, and the Dragonfly project quickly took root.

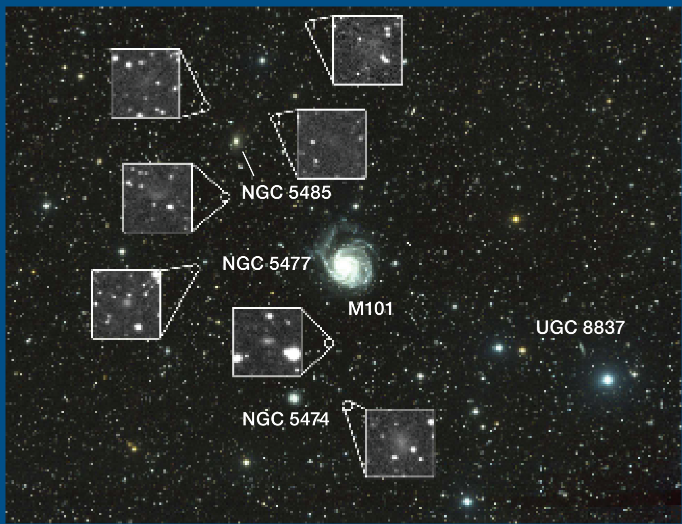
The first system assembled at New Mexico Skies in 2013 consisted of Canon 400 mm f/2.8 lenses attached to individual SBIG STF-8300M CCD cameras riding atop a Software Bisque Paramount ME German equatorial mount as a proof-of-concept experiment. Proving its worth beyond a doubt, it quickly expanded to 5 lenses, then 8, 10, and 24. Currently, a whopping 48 lenses make up two sets of 24 on a pair of Paramount Taurus fork mounts. These two sets of "compound eyes" make up the Dragonfly Telephoto Array, a name bequeathed from their resemblance to the compound eyes of a dragonfly. The name also acknowledges the discovery of the nanostructure found on insect wings that inspired Canon's new nano-coatings as well as van Dokkum's fondness for photographing small creatures.

If a large segmented mirror is considered a single, large-aperture reflector, it's not a stretch to call a large, multi-lens refracting system all pointing at the same target in unison a large refractor. Forty-eight separate 400-mm f/2.8 telephoto lenses operating at full aperture have an effective aperture of almost 1 meter. The focal length, however, is still only 400-mm, and thus the *effective* focal ratio of the Dragonfly system is a staggering f/0.39. This is actually faster than the theoretical limit (f/0.5) for a single optic, making Dragonfly the world's fastest telescope system.

While this is amazing in terms of photographic speed, it is not without its tradeoffs and technological challenges. The system does not perform any interferometry to increase its angular resolution, so it operates at 0.8-arcsecond resolution, about the same resolving power as a 6-inch telescope. That's still a fairly good match to the atmospheric seeing conditions at a decent site.

There is a strong allure to just stacking OTAs or camera lenses together to increase your imaging throughput. Plus, it sounds pretty easy, right? Just keep adding lenses. But the success of Dragonfly would not have been possible without the help of Mike and Lynn Rice, who solved some very significant logistical problems.

EIGHT EYES Dragonfly briefly operated with 8 lenses, producing the team's first discoveries of dwarf galaxies around M101 (inset). Current galaxy-formation models predict that large galaxies should be surrounded by hundreds of faint dwarf galaxies. Of the 7 that Dragonfly detected, only 3 were found to orbit the large spiral.



Think about all the things that can go wrong in an evening with just a single system — and then multiply that by 48. With decades of experience keeping systems going with as little intervention as possible, Mike Rice guided the growth of Dragonfly from just a few lens/camera combinations to the behemoth it is today.

Perhaps the biggest challenge was controlling 48 imaging systems simultaneously. A single computer controlling 48 cameras and focusers was simply not practical. Instead, each camera-and-lens combination has its own Intel Compute Stick computer running a special version of *Microsoft Windows 10*. One computer controls one camera and one focuser. Each of these computers connects via gigabit Ethernet to a master computer that sends commands to the individual units, all running independent copies of Software Bisque's *TheSkyX Professional* with camera control. Abraham wrote specialized automation code to create the scripts and send commands to each computer. All 48 systems operate as if they are lone instruments taking pictures on their own mount. Tell all 48 of them to run their autofocus routine, and they are off, all focusing in parallel. If there is a problem with one lens, only that one system is affected. Even if a catastrophic failure occurs with one optic, 47 other optics can still collect data.

▲ **NEW CAGE** The next step in the expansion of the array was to add two more optics and fabricate a custom cage that allowed for precise aiming of each lens while minimizing flexure between each instrument.

So how do you focus with a telephoto lens on a CCD camera? Each lens is connected to an SBIG CCD camera using a motorized adapter by Birger Engineering Inc. (**birger.com**) that can be controlled via a serial RS 232 interface. A custom focusing script and algorithm coded by Abraham focuses each lens independently.

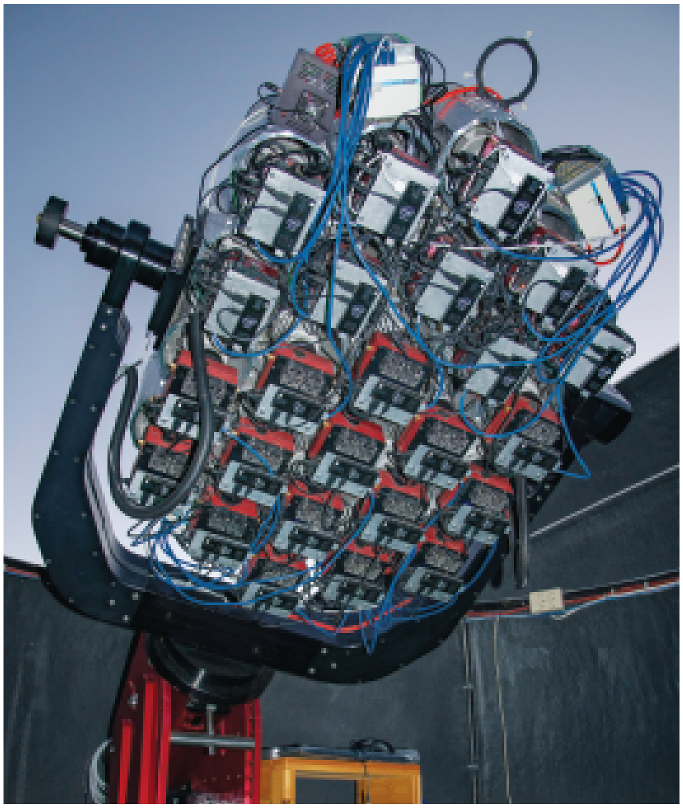
With 48 separate computers, cameras, focusers, optics, and power supplies, all networked together and mounted in a cage system that minimizes flexure, Dragonfly starts to sound more like a pretty sophisticated system with a world of complexities that need to be managed effectively. Managing the cables alone takes a considerable amount of planning and forethought. Nevertheless, the concept is wonderfully scalable, as there is no real limit to the number of "eyes" that can be deployed. There is, of course, no requirement that they all be in the same location either — they could be deployed anywhere in the world.

The next problem that also scales well is the vast amount of data coming out of Dragonfly. Four-dozen cameras taking images every 10 minutes will accumulate a significant amount of data that needs to be reduced (calibrated in amateur imager-speak). All data reduction takes place in the cloud. Compute Canada (**computecanada.ca**) provides cloud-based computing resources to researchers in Canada, and at the request of Abraham or his graduate students, thousands of virtual machines spring into life, crunch through the data, then graciously disappear when finished, leaving behind a pile of data ready for further analysis. This is truly parallel processing at its finest.

Data and Discoveries

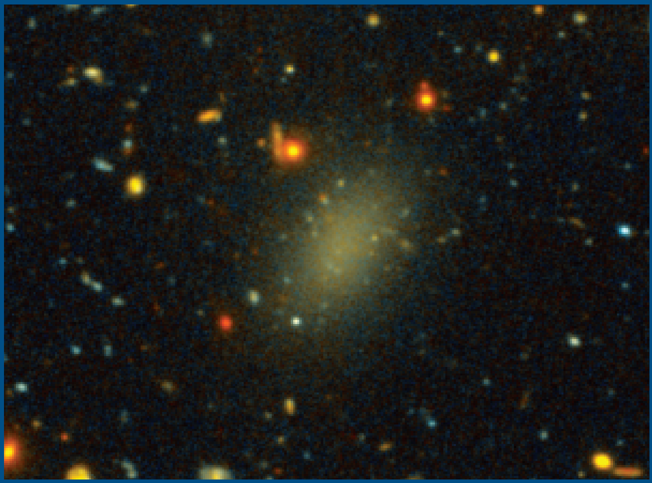
While Dragonfly is an impressive technical instrument in its own right, let's not forget what it was designed to do: detect ultra-low surface brightness objects and structures around galaxies. Abraham and van Dokkum are not theorists but observers. To help them interpret Dragonfly's discoveries, they invited Harvard University Professor of Astronomy Charlie Conroy to join the team.

Among the first published results was an effort to spot a tenuous "stellar halo" predicted to exist around all massive galaxies. To their surprise, the stellar halo around their first target was found to be incredibly faint — far fainter than predicted by models. This narrative (later confirmed by the



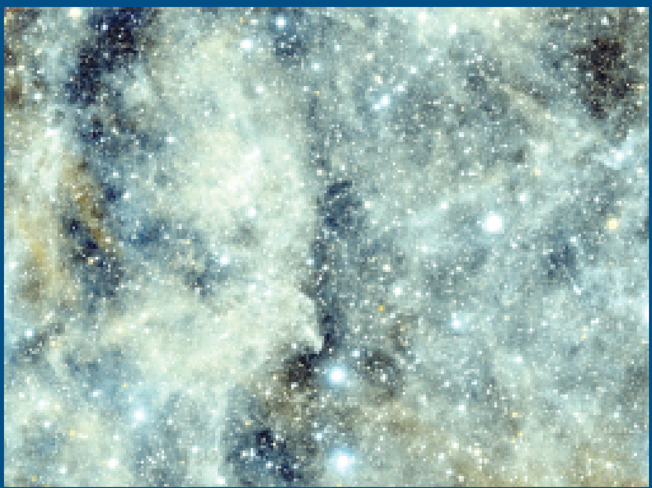
▶ **CORD MANAGEMENT** Powering each array's 24 computers, CCD cameras, and electric focusers requires careful planning.

BACKSIDE: DENNIS DI CICCO



▲ **DARK MATTER** Discovered while studying the Coma Cluster (Abell 1656), DF 44 is an ultra-dim dwarf galaxy that is 99.9% dark matter.

▲ **ALL MATTER** In contrast to DF 44, Dragonfly 2 (NGC 1052-DF2) was found to contain virtually no dark matter.



▲ **CIRRUS EVERYWHERE** Besides its galaxy research, Dragonfly is finding faint nebulosity, sometimes known as galactic cirrus or integrated flux nebula, virtually everywhere it targets.

Hubble Space Telescope) has been repeated over and over with Dragonfly: The array keeps finding surprises that challenge current models of galaxy formation and that astronomers need to follow up on using the world's largest telescopes.

In another early example, Dragonfly undertook an investigation of dwarf galaxies surrounding M101 (*S&T:* Sept. 2015, p. 16). Current models predicted that there should be hundreds of leftover dwarf galaxies in orbit around M101. Although Dragonfly discovered 7 dwarf galaxies, the data suggests that only 3 of those were orbiting the galaxy, while the other 4 were not.

"The fun of Dragonfly is that almost everything you turn it to seems to yield something new," says Abraham. As part of another survey, Dragonfly turned its eyes to the nearest large galaxy cluster, the Coma Cluster (Abell 1656), which is among the most well-studied areas in the extragalactic sky. Surely, there was nothing new to find there. But what Dragonfly uncovered there was even more surprising.

In the case of Abell 1656, Dragonfly detected a substantial population of large but faint galaxies, a class of objects that have come to be known as *ultra-diffuse galaxies*. These objects are extremely hard to detect, and they didn't exist in the leading models of galaxy formation. Objects similar to ultra-diffuse galaxies have been seen before but only as very rare oddities. In its first observation of the Coma Cluster, Dragonfly discovered 47 of them *by accident* (*S&T:* Mar. 2015, p. 12). Using the Dragonfly data as reference for recalibrating their search, the Subaru 8-meter telescope soon turned up over 700 more! Understanding the nature of these mysterious galaxies has turned into a major focus for observational astronomers.

Abraham points out that astrophysicists knew about low surface brightness galaxies similar to ultra-diffuse galaxies for decades before Dragonfly rekindled interest in them. But

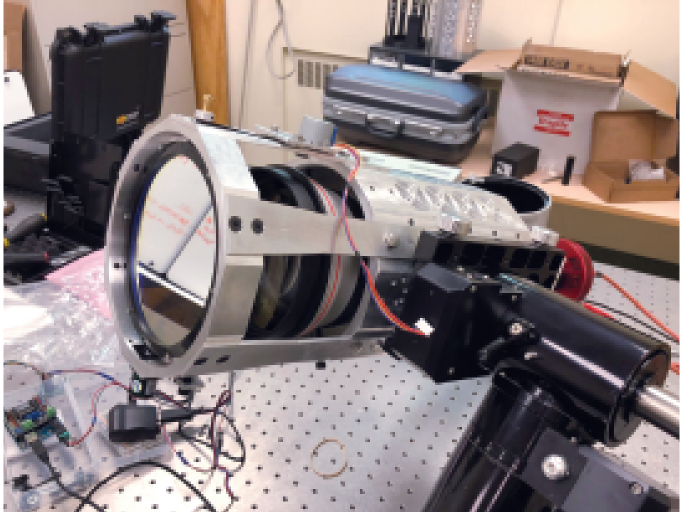
▼ **DOME HOMES** Both Dragonfly 1 and 2 reside in Astro Haven clamshell domes at the New Mexico Skies telescope hosting facility.

DARK MATTER: P. VAN DOKKUM / R. ABRAHAM / GEMINI OBSERVATORY / AURA; MATTER: P. VAN DOKKUM / R. ABRAHAM / STSCI; DOMES: DENNIS DI CICCO the significance of the current new focus on the low surface brightness universe cannot be understated. It's not simply that a new type of galaxy was discovered, but that these previously hidden galaxies are now turning up all over the place and in great numbers. As is typical in science, one new answer generates even more interesting follow-up questions. Some 20% to 30% of these newly discovered galaxies have enormous populations of very luminous globular clusters as well. Is there a relationship between globular cluster abundance and dark matter? Follow-up spectroscopic observations on ultra-diffuse galaxies using the Keck telescopes on Mauna Kea show this to be the case.

The best example of a large ultra-diffuse galaxy with enormous amounts of dark matter but hardly any stars is Dragonfly 44 in the Coma Cluster, which is 99.9% dark matter. On the other hand, Keck observations reveal that another newly discovered galaxy near NGC 1052, DF2, contains almost no dark matter at all, in spite of having a huge population of ultra-luminous globular clusters. It is becoming increasingly clear that galaxies in the ultra-diffuse domain have as much diversity as the more readily visible galaxies we've been detecting since the advent of astrophotography. They are also challenging our current assumptions and raising new questions about galaxy formation.

While astronomers can use existing instrumentation to detect all of these things, Dragonfly simply makes it far easier. The array is producing groundbreaking discoveries and observational confirmations very early in its career. How long would we have had to wait to find ultra-diffuse galaxies in the Subaru data had it not been for the pioneering work by the Dragonfly array pointing the way?

▼ **TEAM PLAYERS** Dragonfly Telephoto Array team members and graduate students seen from left to right: Roberto Abraham, Pieter van Dokkum, Jielai Zhang, Shany Danieli, Lamiya Mowla, Deborah Lokhorst, and Allison Merritt.



▲ **COMING SOON** A 6-element "Son of Dragonfly" array will utilize full-aperture narrowband filters in front of each lens to search for faint hydrogen emissions predicted to connect galaxies.

It's clear from this example alone that Dragonfly's parallel-processing approach to astronomical research can supplement and enhance the work of the world's largest instruments. Dragonfly seems to make finding otherwise challenging objects incredibly easy, acting in some cases as a kind of finderscope for larger telescopes, which then know where to look. Think of Dragonfly as a bloodhound for ultra-dim targets.

What's Next?

Dragonfly has garnered a lot of attention in the astronomical community, inspiring similar projects. In development are the Huntsman Telephoto Array at Siding Spring Observatory in Australia, as well as smaller experimental arrays that both the University of Alabama and York University are assembling.

As for Dragonfly itself, there are several new and exciting projects that go well beyond the team's original vision. The Naiad Array in development will effectively be the "Son of Dragonfly." This 6-lens array will have full-aperture, 6-inch narrowband filters. Astronomers will use the array to look for weak luminescence from hydrogen gas trapped by dark matter filaments in the cosmic web, a predicted (but not yet observed) connection between all galaxies in the universe. In the meantime, researchers are using the main array to undertake a wide-area survey in a search for very nearby ultra-diffuse galaxies and are producing exciting new results in a range of other areas. This includes looking for light echoes from past supernovae, which would reveal the type of supernova responsible for the explosion long after it happened.

There's no question that results from Dragonfly are changing our understanding of the universe, revealing fascinating new details on the structure and origin of galaxies, and will continue to do so for years to come. Is this a new paradigm for small, powerful, low-cost astronomical observatories? Probably, and it will be exciting to see how Dragonfly and other projects inspired by it evolve in the coming years. You can follow their progress at **dragonflytelescope.org**.

■ **RICHARD S. WRIGHT, JR.** is a senior software engineer for Software Bisque. Follow his *Sky & Telescope* astrophotography blog at **https://is.gd/imaging**.