Quantum Optics: Applications in Astronomy

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Abstract

Detailed observation of faint astronomical sources is a challenge for astronomical instrumentation, and methods for decreasing the inherent limits due to diffraction or increasing the instrumental sensitivity typically require ever-increasingly large and expensive telescopes, either ground-based or space-based. Recent developments in quantum optics, both on the instrumentation and theoretical sides, have caused several researchers to suggest the incorporation of inherently quantum mechanical ideas to improve observational capabilities for astronomical purposes. I summarize three recent developments in this area: the use of quantum repeaters, developed to facilitate quantum information, to remove upper bounds on the size of interferometer baselines; the use of squeezed states to reduce photon shot noise to make the measurement of gravitational waves through interferometry feasible; and, most recently, the suggestion that quantum cloning can allow astronomers to increase angular resolution past the diffraction limit.

I. Introduction

In the five hundred years since the invention of the telescope, astronomers have improved these instruments dramatically from the first designs used by Galileo. As astronomers gaze further out into the cosmos, the need for larger telescopes grows. One reason is simply that as the size of the telescope increases, so does the number of photons it can detect from astrophysical sources, increasing its sensitivity. Since this can also be done simply by increasing the exposure time, this problem can be overcome without building large telescopes. However, the second reason is that the angular resolution increases with the size of the telescope aperture. Classically, the angular resolution is limited due to diffraction, as described by the *Rayleigh Criterion*

$$\theta = 1.22\frac{\lambda}{D}, \quad (1)$$

where θ is the angular separation that can be accurately measured, λ is the wavelength of light, and D is the lens diameter. Clearly, as D increases, the angular resolution increases. For astronomers attempting to measure distant star radii or binary systems, making more accurate parallax measurements, or obtaining detailed images of faraway galaxies, this is a necessary goal. From a quantum mechanical point of view, this diffraction limit can be linked to the Heisenberg uncertainty principle. The larger the aperture, the greater the uncertainty in the photon's position, so its momentum uncertainty decreases in accordance with $\Delta x \Delta p \geq \frac{\hbar}{2}$. Since the photon's momentum contains the vital information about its origin on the source, gaining more certainty in this gives the important information in determining angular resolution.

Currently, at least three "extremely large telescopes" are in the preliminary stages of planning or construction that, by using very large lenses with adaptive optics, hope to greatly improve our ability to observe distant space with very high resolution. Two of these, the European Extremely Large Telescope and the Giant Magellan telescope, will be constructed in the Atacama desert in Chile; a third, the Thirty Meter Telescope, will be constructed on Mauna Kea in Hawaii. Out of these three,

two have estimated costs in excess of one billion dollars, a number which is only expected to rise. This prohibitive cost motivates new research into novel ways of getting around this diffraction limit.

A different, significantly cheaper, way to cope with this limit has been through the use of interferometers to observe distant objects, whereby astronomers use the interference pattern created by bringing two different telescope measurements together to gain information about the source. It is a version of this technique that Hanbury Brown and Twiss were pioneering when they measured photon bunching that led to an increase in interest in the photon nature of light that greatly added to our knowledge of quantum optics. However, the angular resolution is still dependent on the size of the interferometer. Increasing the size of an interferometer is cheaper than increasing telescope size, but this length cannot increase without bound for reasons other than financial ones. Two major constraints on the interferometer baseline size are phase fluctuations and photon loss.

Since the issues present with attempting to increase the angular resolution of telescopes deal with the quantum nature of light, it is unsurprising that the study of this light might be useful in fixing the difficulties mentioned here. I address two recent suggestions for ways to resolve these difficulties. One approach to improve the angular resolution of average size single telescopes was recently detailed by A. Kellerer at Durham University. Her approach involves the creation of non-deterministic imperfect photon clones, which are detected following the triggering of a quantum non-demolition measurement. This approach will be described in the next section.

For interferometer experiments, a suggestion by Gottesman, Jennewein, and Croke involves the use of quantum repeaters, developed to facilitate quantum information systems to "transmit" photons over long distances, to extend the lengths of the interferometer baseline potentially without bound. Their approach, as well as the many potential difficulties in building such a system, will be described in the second section.

Finally, as one more example of the recent interaction between the areas of astronomy/astrophysics and quantum optics, I will briefly discuss a recent experiment by the LIGO collaboration demonstrating the significant increases in gravitational wave sensitivity through the use of squeezed states.

These three examples will serve to describe the fascinating new ways that astronomy, with its almost incomprehensibly large length scales spanning thousands or even millions of light years, can intersect with and benefit from developments from the quantum world, with its microscopic length scales.

II. Beating the Diffraction Limit with Quantum Cloning

As mentioned in the introduction, in order to achieve greater angular resolution the lens aperture size must be increased. Quantum mechanically, this increases the uncertainty in position - it is more difficult to localize the photon, so its initial propagation direction, which allows for measurement of its origin, can be measured more accurately. The visual effect of this lack of knowledge about its momentum is diffraction, which causes the image to be blurred.

To better understand how the suggested method will help to reduce the effects of diffraction, it is helpful to consider how diffraction effects can be reduced in the observation of a point source. Since every detected photon can be considered to come from the same source, the mean position of the incoming photons can be determined more accurately simply by measuring more photons. If N_1 photons are measured, the standard deviation of this distribution will equal $1/\sqrt{N_1}$ of the standard deviation of an individual photon position. Clearly, then, the standard deviation can be decreased by measuring more photons.

For an extended source, however, simply detecting more photons is not useful since it is impossible to identify photons originating

from the same point on the extended object. It is for the observation of these sorts of objects that this proposal seeks to improve.

The idea is to place a photo amplifying medium consisting of excited atoms in the pupil plane of the telescope. Since these will spontaneously emit photons, doing so will require some method of extracting the important signal from this added noise. One way of removing much of the noise is to place this setup within a cavity resonant in the field-of-view; thus, since many of the spontaneously emitted photons will not be in this direction, they will exit the cavity and not be detected. Still, there will be a significant amount of noise from spontaneous emission in the field-of-view direction; this noise can be greatly reduced by using a quantum non-demolition measurement of the incoming photons from the source to trigger a measurement and extract the key data. This will be described shortly; first, we must examine how this system will help to reduce diffraction. Incident photons from the astrophysical source will cause stimulated emission in the excited atoms; a non-deterministic fraction of these photons are clones of the incoming photon - otherwise this would violate the quantum no-cloning theorem. For a given photon, there might be $N-1$ photons emitted in the cavity due to stimulated emission. These must all be detected simultaneously in order to pinpoint what detections come from a single astrophysical photon, so a coincidence detector can be used to identify what detected photons are clones of this photon. Now, since a total of N photons are known to have originated from a single source, the mean of their detected positions gives a more accurate measurement of the true position, just like how the location of a point source can be pinned down more accurately by averaging over a number of detections. Another way of thinking about this is in terms of the photon wavefunction: when a photon is detected, it will collapse, with probability given by the square of its wavefunction, to some position, P', that might be quite different than its true position - this is yet another way of thinking about diffraction on a quantum level. However, if we can create an ensemble of photons with the same wavefunction through this stimulated emission process, then we can easily measure the expectation value of this state and get a more accurate measurement of its true position.

The sizable increases in angular resolution that this method brings about will be useless, however, if the noise added by the spontaneous emission of photons from the excited atoms is not removed. As can be seen in the figure, a proposal for eliminating this noise is to perform a quantum non-demolition measurement on the incoming photons. This sort of measurement, a recent possibility also coming out of the field of quantum optics, is one where the photon is able to change the polarization of an atom without destroying the photon due to absorption. By measuring the polarization of the atom through Raman interferometry, this can be used as an ideal trigger system for the coincidence detector.

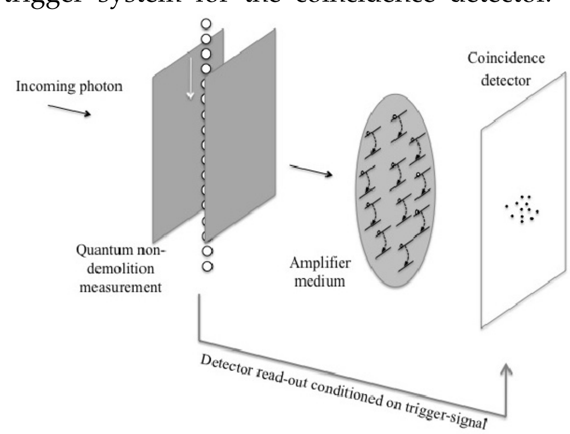

Figure 1: Instrumental Design

As the next two figures show, numerical simulation of this setup demonstrate the effective gains in angular resolution that can be achieved. 35 photon copies were used, improving the angular resolution by a factor of 6. The first image demonstrates how the image would appear without this instrumentation - diffraction effects completely ruin the angular resolution needed to accurately observe individual stars. The middle image demonstrates the importance of the coincidence detector. Without it, all that the amplifier medium does

is wash out the image further since the averaging of cloned photons cannot occur reliably. However, as the final image shows, if only simultaneous detections are recorded, averaged over, and then their mean position (corresponding to the "true" position) is imaged, then the angular resolution is drastically improved.

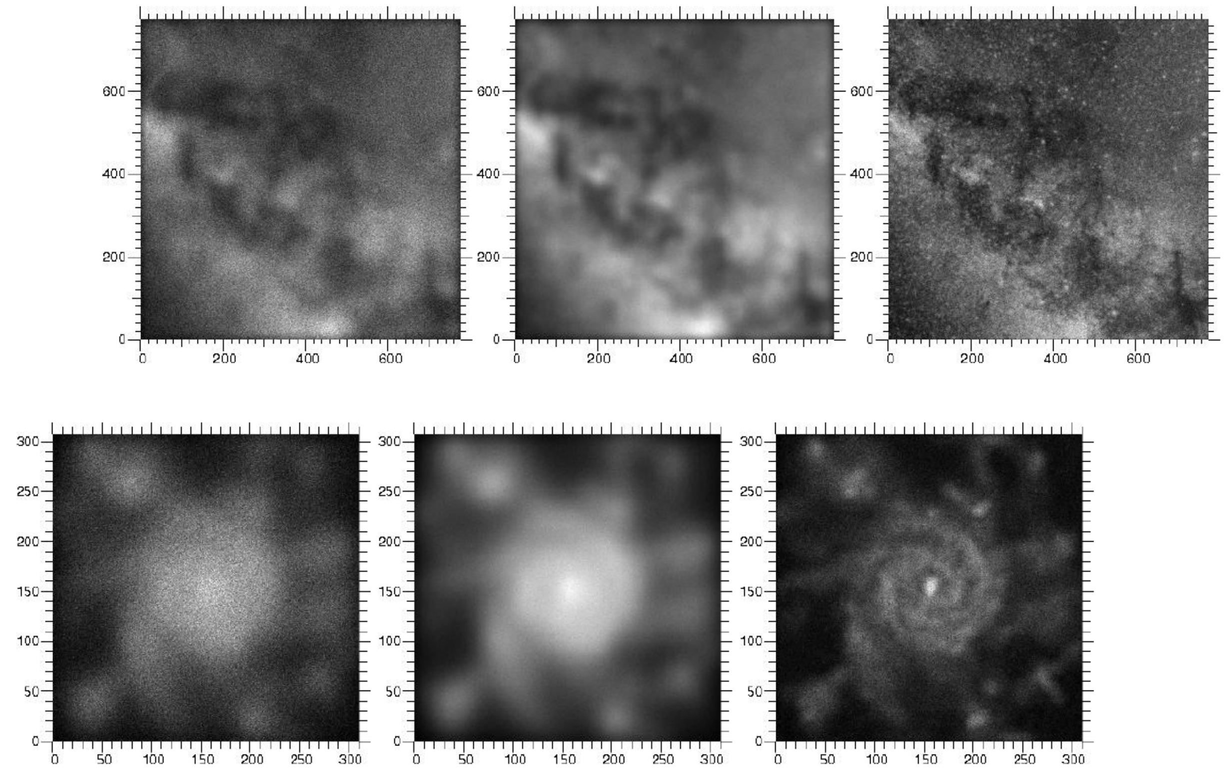

Figure 2: Numerical simulations of the improved angular distribution through this effect.

Of course there are significant technological difficulties that must be overcome before this sort of measurement will be feasible. The two biggest difficulties are that the detector must have a very high timing precision in order to detect simultaneous events individually, and the walls of the cavity must be very reflective, leading to difficulties in making sure that the incoming photon enters the cavity. Additionally, the non-demolition measurement must be highly consistent, especially for faint sources. The biggest tradeoff in solutions to these technological difficulties is in the sensitivity or in the spectral bandwidth, both of which require longer exposure times. Nonetheless, this new application of these quantum optics technologies and measurement systems can encourage increased effort in making higher resolution devices.

III. Longer-Baseline Telescopes Using Quantum Repeaters

Interferometry is another essential tool for astronomers seeking to make observations requiring high angular resolution. Two telescopes, a distance b (known as the baseline) apart, both measure light from a distant source. They then combine these measurements and, based on the relative phase shift between these two sources,

very accurate measurements of the source's position can be made. Since the phase difference depends on the baseline, the greater the baseline, the simpler it is to accurately measure the phase difference. Additionally, if the baseline is adjustable, or an array of telescopes are used, then the brightness distribution of the source can be accurately determined, another quantity of interest.

However, the amount of information that can be distracted from this interferometry is constrained by the difficulties involved with transporting the different signals from the two telescopes so that the interference pattern can be measured. It is very difficult to transport single photons over long distances without either losing them along the way or introducing extra random phase shifts. Thus, it is critical that this problem be addressed.

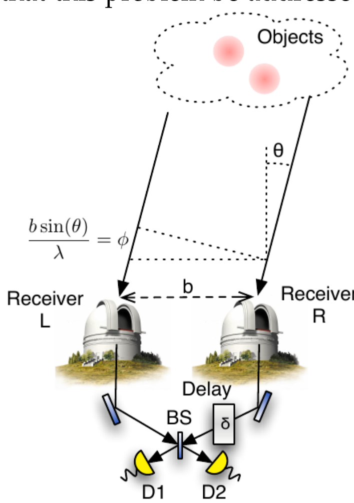

Figure 3: Basic setup of a direct detection interferometer

Once again, the field of quantum optics has an answer. Since one of the critical areas in making quantum information possible is in transporting the signal photons over long distances, this is not a new issue. The authors of this paper suggest using creating an entangled state that can then be transmitted to the receivers, ensuring that the photons from the astrophysical source are not lost along the transmission line. If the entangled state is lost, another can always be sent. Once one is received, it can be checked to ensure that it was transmitted correctly, and then the interference experiment can be done using quantum teleportation with this entangled state, using the techniques developed in chapter 14 of Fox.

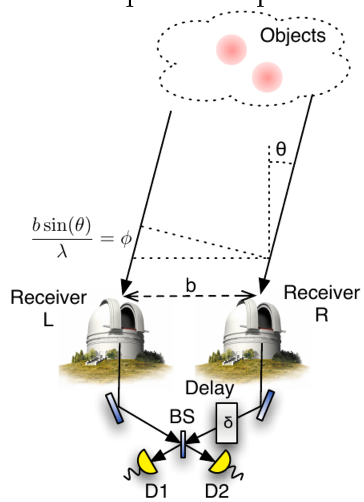

Figure 4: Performing an interference measurement using an entangled state.

Of course, transmission of the entangled state has as much possibility for loss or decoherence as the original photons detected from the source. This is where the idea of using quantum repeaters enters. A network of repeaters could be constructed that could transmit entangled states, effectively connecting each node along the way so that an entangled state could be transmitted, in principle, an arbitrarily long distance.

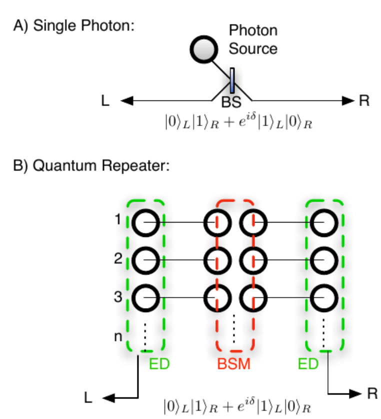

Figure 5: How a repeater uses quantum relays and entanglement distillation to entangle dis-

tant receivers

As with the quantum cloning technique, this suggestion is only a future possibility. Several major technical problems exist: quantum repeater protocols must be developed that can produce an extremely high rate of broadband detectors, and, as with the previous proposal, high-efficiency detectors with fast time resolution are required.

IV. LIGO Squeezed States

I will briefly introduce a third area where quantum optics techniques have been proposed for improving astronomical observations, except in this case these techniques have already been applied and success has been demonstrated. The LIGO collaboration has built an earth-based gravitational wave observatory, which uses precise laser interferometry to detect and measure the incredibly tiny strains created by gravitational waves.

Two mechanisms of quantum light that limit the ability of the interferometer to make the highly precise measurements required are photon shot noise and radiation pressure noise. Both of these effects are due to the quantum vacuum fluctuations.

In brief, if squeezed states rather than coherent states are used, then the shot noise can be reduced, allowing for more sensitive detection bounds. The idea here is that a coherent state, which is one that has the minimum uncertainties allowed by the Heisenberg uncertainty principle, is actually not the most advantageous state here. A squeezed state, which trades certainty in one variable (in this case, the in-phase quadrature) for added uncertainty in another, can allow experimenters to do measurements of this especially certain variable that dramatically reduce shot noise from the vacuum field.

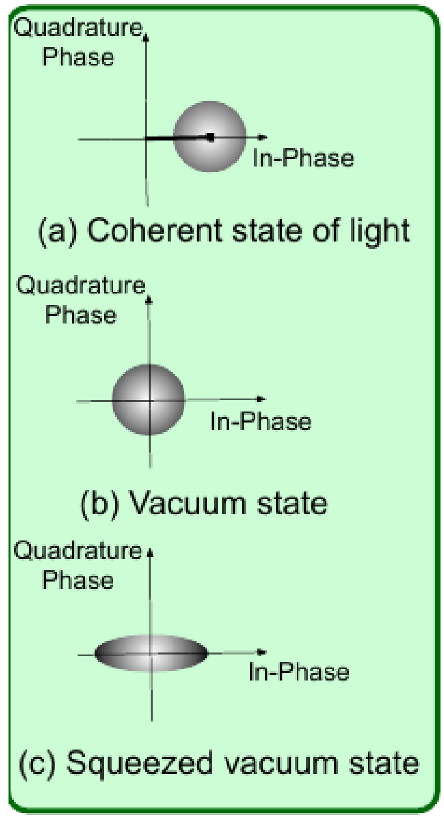

Figure 6: Squeezed/Coherent light.

The details of how these squeezed light forms are created and how they can decrease the noise below that allowed by the shot noise can be found in chapter 7 of Fox. Here I will just show the results of the LIGO group's measurements of the increased sensitivity given by using squeezed states. They report improvements up to 2.15 dB in the shot noise limited frequency bound, which corresponds to a 28% reduction in the shot noise. This allows for them to make the most sensitive measurements yet of gravitational waves, and this method brings about none of the difficulties that are present with other solutions to the shot noise problem. Figure 7 shows their data, clearly demonstrating that the squeezed light is not only more sensitive to strain than none-squeezed light, but that it truly does result in noise significantly under the shot noise limit.

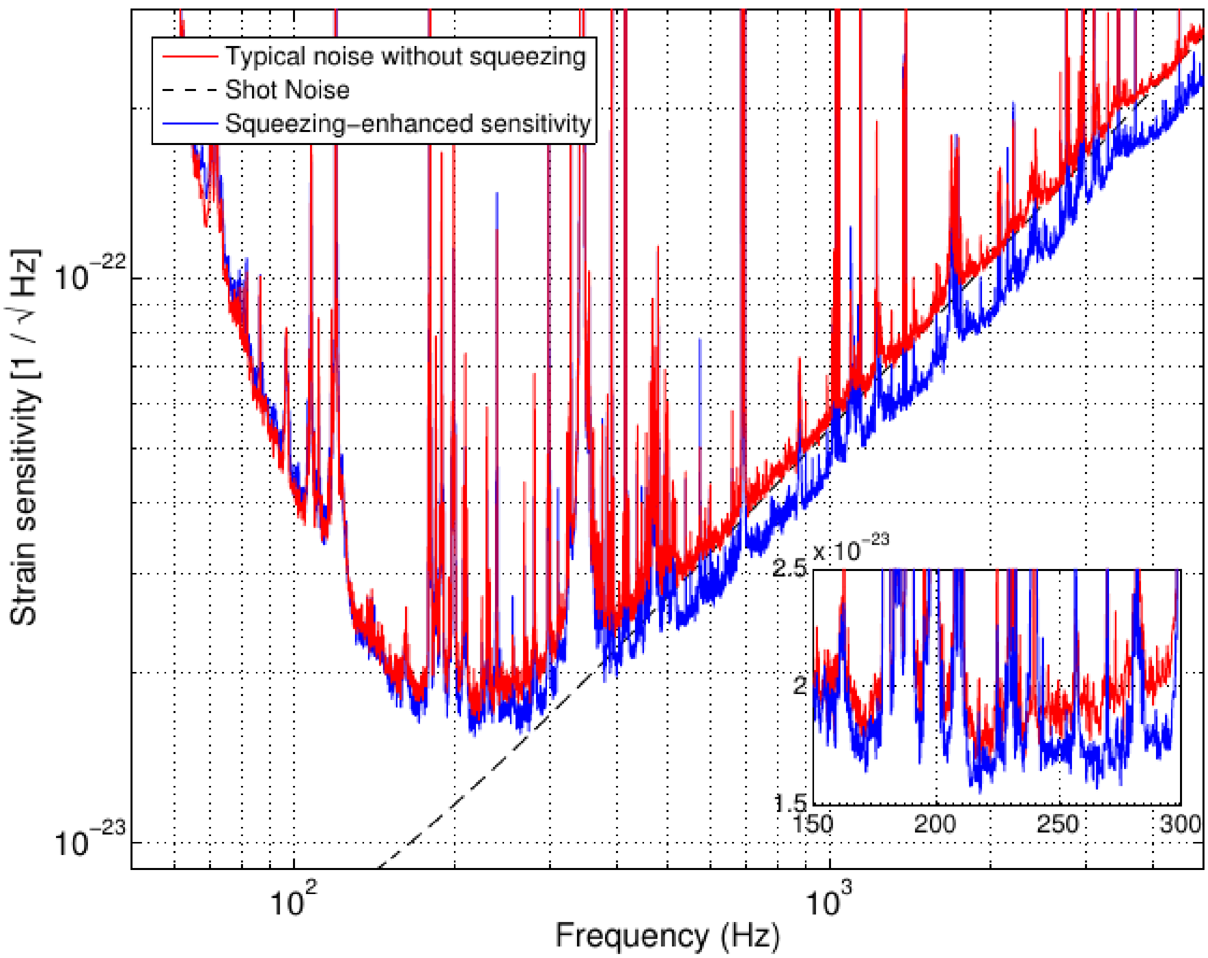

Figure 7: LIGO sensitivity data demonstrating the benefits of using squeezed states

V. Conclusion

In conclusion, these three articles all demonstrate possibilities for using the recent developments in quantum optics and quantum information theory to dramatically improve astronomical observational capabilities. Quantum cloning and light/matter interactions can be used to increase the angular resolution of a single telescope of moderate size, which would have significant financial benefits since these smaller telescopes could then resolve objects only resolvable with larger, hugely expensive new telescopes. Entangled states, passed along networks of quantum repeaters, would eliminate the difficulties inherent in sending photons from galactic sources along noisy transmission lines in order to perform interference experiments, thus paving the way for interferometer baselines of very large distances that would greatly increase the accuracy in interferometer measurements. Both of these suggestions, while theoretically possible, require significant advances in technical abilities before they can be realistically applied. However, as the field progresses and the possibilities of these techniques become more widely applicable, it is very likely that attention to these problems will increase and rapid improvement will happen soon. The LIGO measurements give

an example of this interplay between quantum optics and sensitive astronomy measurements that has been experimentally tested and shown to work, and the progress made in this area should be an encouraging push for others to move forward in tackling the other problems.

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