Astrophysically sourced quantum coherent photonic signals

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Stimulated emission is shown to be robust in stars. Through Bose enhancement this produces quantum states of aligned, monochromatic photons somewhat similar to a laser. The probability of creating such states is computed. We show that from the solar corona such quantum states would propagate outside of the solar region and through the Solar System without decoherence. For a 1-m^2 test detector at the distance of the Earth from the Sun, we estimate rates of such quantum states in the few per second thus potentially detectable. The same process should lead to such quantum states also arriving from stars at interstellar distances.

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I. INTRODUCTION

Recently it was observed by one of us [1] that photons in certain frequency bands can traverse interstellar distances, without their initial quantum state decohering. This fundamental point has potential far reaching consequences for astronomical observation. That paper already noted applications both for interstellar quantum communication, with further work along that line done in [2], and possible detection of quantum coherent signals from astrophysical sources. By quantum coherence of photons we mean very simply N photons in some specified quantum state, which in this paper in particular means they are all identical, so with the same momentum $\vec{k}$ and polarization s. This, which we will call an N-identical photon state, is suggested as a possible type of quantum coherent photonic signal. In this paper we identify a specific mechanism in stars and their atmosphere that can create such states and examine the possibility for observing these quantum coherent photon signals at distances far away from emission.

The elementary process creating an N-identical photons state is stimulated emission. When a photon in state $|1_{\vec{k},s}\rangle$ impinges upon an atom that is in an excited state of the same energy as itself, an emission from the atom is possible that then leads to two photons in the same state, $|2_{\vec{k},s}\rangle$. This two-photon quantum state will be identified as a two-identical photons state. The process can repeat by impinging these photons on another atom to create a three-identical photons state with a Bose enhancing factor and so forth. We observe that in the stellar environment there should be a ubiquitous production of such N-identical photons states, especially the simplest two-photon process.

Deep enough below the surface of the star, these states will quickly decohere through interactions. However, if such a stimulated emission event occurred above the surface in the stellar atmosphere, then it is possible these photons could escape with their quantum state intact.

In this paper we will examine the details of such stimulated emission events inside the stellar environment. We will then examine the mean-free path (MFP) of photons both in the stellar environment as well as in the interplanetary region of the Solar System and assess the flux of such photonic quantum states that could be measured. We will then discuss ways in which such states could be detected both directly and indirectly.

Here, we identify all potential sources of decoherence and show that these effects are small. We will take a first-principles approach and look directly at the interactions of the photons with all particles in the medium and show the mean-free paths from such interactions are much longer than the distances the photons are required to traverse, often orders of magnitudes longer. Of course there may be some residual decoherence and before attempting experiments that would need to be understood. Standard methods such as density matrix, master equation etc., could be

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employed to quantify these higher-order effects. The purpose of this first paper is to highlight the dominant physical effects and establish that to zeroth order decohering effects are negligible.

II. MECHANISM OF STIMULATED EMISSION

Let us start with a brief review of the mechanism of stimulated emission. A more detailed discussion of it can be found in textbooks such as [3]. To calculate the transition probability of stimulated photon emission, using Fermi's golden rule gives the matrix element $\langle (N+1)_{\vec{k},s}| \otimes \langle \Psi_f|H_I|\Psi_i\rangle \otimes |N_{\vec{k},s}\rangle$, where $|\Psi_i\rangle$ and $|\Psi_f\rangle$ are initial and final states of the atom, respectively, $|N_{\vec{k},s}\rangle$ is the N-photon state in Fock space with momentum $\vec{k}$ and polarization s, and H_I is the interaction Hamiltonian between the electromagnetic field and atom. Such a matrix element will lead to a quantum mechanical Bose enhancement factor such as $\langle (N+1)_{\vec{k},s}|\hat{a}^\dagger_{\vec{k},s}|N_{\vec{k},s}\rangle = \sqrt{N+1}$, which means that for a state with a high number of photons, there is an enhanced chance of stimulated emission of one more photon in the same state.

A semiclassical approach such as the one in [4] leads to an expression for the cross section of the stimulated emission of a single atom of the form

$$\sigma = \frac{2\pi^2}{3n\epsilon_0 ch}|\mu|^2 \nu g(\nu - \nu_0). \tag{1}$$

Here, n is the refractive index of the medium, μ is the magnitude of the time-independent electric dipole moment between the initial and final wave functions of the atom, ν is the frequency of the photon, and $g(\nu - \nu_0)$ is the line-shape function with width $\Delta\nu_0$. In our discussion, we will choose the Lorentzian line-shape function, though note that the results we find are comparable to those using other line-shape functions such as Gaussian.

The stimulated emission process needs the electric dipole moment, which can be extracted from the measured spontaneous emission rate. A textbook expression for the spontaneous emission rate reads [4]

$$A = \frac{16\pi^3\nu_0^3 n|\mu|^2}{3\epsilon_0 c^3 h}, \tag{2}$$

with experimental values readily available on the NIST Atomic Spectra Database [5]. The dipole moment μ appears both in the cross section (1) of stimulated emission and in the rate of spontaneous emission. Thus, we can express it in terms of the measured rates A without an explicit calculation. This allows us to write Eq. (1) now as $\sigma = \frac{\lambda^2}{8\pi n^2} g(\nu - \nu_0)A$. Substituting the peak value at ν_0 of the Lorentzian line-shape function, $g(\nu_0 - \nu_0) = 2/(\pi\Delta\nu)$, into the expression for the cross section leads to the stimulated-emission cross section at wavelength λ_0 of $\sigma_0 = (\frac{\lambda_0}{2\pi n})^2 \frac{A}{\Delta\nu}$. As can be seen, the stimulated-emission cross section depends on four quantities: the wavelength λ_0, refraction index n of the material, frequency width of the emission $\Delta\nu$, and rate of spontaneous emission A. Using the NIST data for the numerical values of A allows us to calculate cross sections of any stimulated-emission line from any ions. Reexpressing the frequency width $\Delta\nu$ to wavelength width $\Delta\lambda$, we have

$$\sigma_0 = \left(\frac{\lambda_0}{2\pi n}\right)^2 \left(\frac{A\lambda_0}{c}\right)\left(\frac{\lambda_0}{\Delta\lambda}\right). \tag{3}$$

Here, $A\lambda_0/c$ gives the ratio between the wavelength of the photon and the length the photon can travel during the timescale of spontaneous emission. Moreover, $\lambda_0/\Delta\lambda$ gives the ratio between the wavelength of the photon and the linewidth.

III. N-IDENTICAL PHOTON STATE PROBABILITY FROM STIMULATED EMISSION

Let us assume that we have an initial one-photon state $|1\rangle$ at one side of a layer of medium of thickness L, filled with atoms of type a, with number density n_a. This initial single-photon state $|1\rangle$ travels through the layer from $x = 0$ to $x = L$. By using coordinate label x, we are not trying to localize the photon but only want to find the probability of a $|2\rangle$ state, a $|3\rangle$ state or in general, an $|N\rangle$ state created through stimulated emission, if any measurement is performed at x.

Denote by $P(x, N)$ the probability of finding an $|N\rangle$ state at distance x; then, the probability of finding an $|N+1\rangle$ state at distance $x + dx$ becomes $P(x + dx, N + 1)$. The relation between $P(x + dx, N + 1)$ and $P(x, N)$ is

$$\begin{aligned} P(x+dx, N+1) = P(x, N+1)[1 - (N+1)n_a\sigma_0 dx] \\ + P(x, N)(N n_a \sigma_0 dx). \end{aligned} \tag{4}$$

On infinitesimal scale dx, finding $|N+1\rangle$ at $x + dx$ includes two mutually exclusive events. The first event is finding $|N+1\rangle$ at x which carries probability $P(x, N+1)$ and then the $|N+1\rangle$ state does not induce stimulated emission from x to $x + dx$, which carries probability $1 - n_a\sigma_0(N+1)dx$. As we discussed above, the probability of a single stimulated-emission event happening after a single photon traveling the distance dx is $n_a\sigma_0 dx$. Both quantum and semiclassical theory indicate that the probability of $|N\rangle$ induces a stimulated emission that is enhanced by a factor of N compared to that of single-photon state $|1\rangle$. Thus, the probability of an $|N+1\rangle$ state inducing a stimulated-emission event from x to $x + dx$ becomes $(N+1)n_a\sigma_0 dx$, which needs to be subtracted to give the probability of not inducing stimulated emission. The second event is finding $|N\rangle$ at x which carries probability $P(x, N)$

and then the $|N\rangle$ state does induce stimulated emission from x to $x + dx$, which carries probability $Nn_a\sigma_0 dx$.

After solving Eq. (4), the probability of finding an $|N\rangle$ state at the other side of the layer is given by

$$P(L, N) = e^{-n_a\sigma_0 L}(1 - e^{-n_a\sigma_0 L})^{N-1}. \tag{5}$$

As a sanity check, one can sum $P(L, N)$ over all N from 1 to ∞ to show that this expression is normalized to 1, independent of L.

IV. RATE ESTIMATION

Next, we estimate the rate of N-identical photons states being created at the solar corona, to then determine the number of such states that could be detectable, ideally in space, on a $1-\mathrm{m}^2$ area near the Earth. We shall consider photons in the optical, UV and x-ray regions.

For the optical, we obtain the rate of $|1\rangle$ states from experimental data from [6]. Then, we calculate the MFP of stimulated emission, to finally compute $P(L, 2)$ using the above formula. For example, Ref. [6] tracks the history of the intensity of the 530.3-nm line, which goes through yearly cycles. However, going to the lower end of the reported intensities, we can still have around 2.4×10^{12} photons arriving on an area of 1 m^2 per solid angle per second. (We conservatively picked a solar cycle of low corona index number plotted in [6] and converted the light intensity to photon number rate.) Hence, $N_1^{530.3} \sim 2.4 \times 10^{12}$ would conservatively count the rate of the $|1\rangle$ state.

Let us now determine the number of $|2\rangle$ states created from stimulated emission. The particle density of the corona is at its lowest at the corona holes; therefore, we conservatively take the particle number density $10^9\ \mathrm{m}^{-3}$ [7] of the corona holes as the density of the entire corona. Schmelz *et al.* [8] give an abundance of iron in the corona of 7.08×10^{-5} with respect to hydrogen. This yields an iron number density of $7.08 \times 10^4\ \mathrm{m}^{-3}$. The ionization fraction of Fe XIV-530.3 nm depends on temperature and peaks at around 0.2 for a temperature $T = 2 \times 10^6$ K based on [9]. Conservatively, we choose the density of Fe XIV at the excited level of 530.3 nm to be $1.0 \times 10^4\ \mathrm{m}^{-3}$.

Given the cross section of stimulated emission $7.585 \times 10^{-25}\ \mathrm{m}^2$, an upper limit of the MFP of stimulated emission of 530.3-nm photons in the corona is $\ell_{mfp}^{530.3} = 1.32 \times 10^{20}$ m. Then, if, based on above, a number $N_1^{530.3} = 2.4 \times 10^{12}$ of 530.3-nm $|1\rangle$ states are emitted on the 1-m^2 area per solid angle every second, the number of $|2\rangle$ states emitted on the same area per solid angle every second can be computed through (5) to be $N_2^{530.3} \sim 145.6$.

Similar calculations show that states equal or higher than $|3\rangle$ are negligibly produced. Although we have conservatively estimated the following quantities including the number of $|1\rangle$ states of 530.3 nm, the overall corona density, the relative abundance of iron in the corona, and the fraction of Fe XIV ions of the specific energy level, there are over 100 $|2\rangle$ states per second per solid angle emitted onto the 1-m^2 area near the Earth.

Turning now to the UV and x-ray emission, we will first estimate the rate of $|1\rangle$ states. Given the available experimental data, we shall use a different approach to compute the densities of the excited ions that will lead to the photons at those energies. For this, the following formula for the intensity of a line will come in handy:

$$I_{\mathrm{line}} = \int_0^\infty I(\lambda)d\lambda = \frac{1}{4\pi}\frac{hc}{\lambda_0}AN_k L, \tag{6}$$

where A is the atomic transition probability we encountered previously, and N_k is the number per unit volume (number density) of excited atoms in the upper (initial) level k. Based on the measurements in [10], the thickness of the corona is about 8 million kilometers, which we will take as the value of L. Reference [11] gives photon intensities of several lines from Fe XII and Fe XIII in the UV range obtained via satellite instruments. With the formula above, we seek to estimate the rate of $|1\rangle$ states from measurements made in [11,12], for UV and x-ray, respectively.

The intensity data of 19.664-nm line of Fe XII in [11] is over 800 $\mathrm{erg}/(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{Å})$ at the peak. We pick a value of 600 (since there is a 19.654-nm peak of 600 and we are unsure of any potential overlap between the two), multiply it with a wavelength width, convert the unit to $\mathrm{eV}/(\mathrm{m}^2\,\mathrm{s})$, and then divide by the energy of 19.664-nm photon in eV. This indicates that $N_1^{19.664} \sim 5.9 \times 10^{14}$ of $|1\rangle$ states arrive on the area per second. The flux data in [12] show that the rate can be $N_1^{1.5} \sim 3.7 \times 10^{10}$ for $|1\rangle$ states of the 1.5-nm line of Fe XVII on the same area.

By reversing (6) and using these intensity and flux data aforementioned [11,12], we find the density of Fe XII and Fe XVII that are excited to the 19.664- and 1.5-nm level, are around $1.9 \times 10^{-5}\ \mathrm{m}^{-3}$ and $2.6 \times 10^{-12}\ \mathrm{m}^{-3}$, respectively. Following the same approach by which we estimated the rate of $|2\rangle$ for 530.3 nm, using $P(L, 2)$, we find the rate of $|2\rangle$ for 19.664 and 1.5 nm to be around $N_2^{19.664} \sim 2.83$ and $N_2^{1.5} \sim 0$ on the same area. As the frequency of the photon increases, fewer $|2\rangle$ states can be created from this stimulated emission process, which is not surprising since the cross section, Eq. (3), goes as ν_0^{-4}.

There are many uncertainties in the understanding of the solar corona, which have allowed us to only make rough estimates of the rates of quantum states from this stimulated-emission process. Nevertheless, we think that the key point is we are finding rates at a few per second in our test detector, rather than on much longer timescales, thus in the realm of being measurable.

V. DECOHERENCE

Having discussed a mechanism to produce this kind of N-identical photons state, one has to wonder how likely it is for it to get to our detector intact without decoherence. As it turns out, the possibility of decohering interactions, in particular for the extreme ultraviolet to the x-ray range, is basically null. In spite of the peculiarities of the corona, current observations do allow us to put strong bounds on MFPs and interaction rates of the potentially dangerous decohering interactions. Spectroscopic studies have shown that there are three distinct "regions" in the corona, dubbed as K, F, and E. The K corona shows no absorption, so there is a continuum of white light that undergoes Thomson scattering, which could affect our quantum coherent photonic state. The optical depth for that interaction is $\tau = \int dr \sigma_{\mathrm{Th}} n_e$, where $\sigma_{\mathrm{Th}} = 6.65 \times 10^{-29}\ \mathrm{m}^2$ is the Thomson cross section and n_e is the electron density in the corona, for which there are several models. Those by Allen and Baumbach [13], and Edenhofer *et al.* [14], respectively, state

$$n_e(r) = \left[\frac{2.99}{r^{16}} + \frac{1.55}{r^6}\right] 10^{14}\ \mathrm{m}^{-3}, \qquad 1.2 \lesssim r < 3, \tag{7}$$

$$n_e(r) = \left[\frac{30}{r^6} + \frac{1}{r^{2.2}}\right] 10^{12}\ \mathrm{m}^{-3}, \qquad 3 < r < 65, \tag{8}$$

where r is in units of $R_\odot$. With that information, we arrive at $\tau \simeq 5 \times 10^{-7}$, which corresponds to an interaction probability of $6 \times 10^{-5}\%$, and a MFP of 10^{17} m, almost 6 orders of magnitude longer than the distance between the Earth and the Sun. Notice that other models will lead to the same order-of-magnitude densities, so our conclusions would be the same [13].

Next, we shall consider potential interactions with the elements in the corona. Naturally, there is less information about the distribution of the atoms throughout the corona, but we can still (over)estimate the probability of each interaction using available data. As previously mentioned, we know the abundances with respect to hydrogen. Unlike before, let us now fix the particle density of the corona to be about $10^{15}\ \mathrm{m}^{-3}$, which we assign to hydrogen. In doing so, the density of each species is overinflated as well as the interaction probabilities. These overestimates are done in order to give us the shortest estimates for the MFPs from decohering processes. Using the abundances reported in [8] and total attenuation cross sections (coherent and incoherent scattering + photoelectric absorption + …) from the XCOM software from [5], we obtained a lower value estimation of the MFP due to photon-hydrogen interactions of $\ell = (\sigma n)^{-1} \simeq 8 \times 10^{11}$ m, which is 5 times larger than the distance between the Sun and Earth. Notice that we chose photon energies ~1 keV, where the cross section always peaks. MFPs of the same order of magnitude are obtained for interactions in the corona with He (4×10^{11} m), Mg (6×10^{11} m), Si (9×10^{11} m), C (10^{12} m), N (2×10^{12} m), Ni (3×10^{12} m), or S (5×10^{12} m). The smallest MFP is obtained for O (2×10^{11} m), whereas for other elements they are larger than those shown above, and among those the strongest interactions are with Al, Cr, and Mn, which in turn render $\ell \simeq 10^{13}$ m. All these MFPs must be combined, with an effective or total MFP given by

$$\frac{1}{\ell_{\mathrm{eff}}} = \sum_i \sigma_i n_i = \sum_i \frac{1}{\ell_i}, \tag{9}$$

where the sum is over all the atoms under consideration. Upon performing this summation, we find

$$\ell_{\mathrm{eff}} = 4.6 \times 10^{10}\ \mathrm{m}. \tag{10}$$

This value lies within an $\mathcal{O}(1)$ factor of the distance between the Sun and the Earth, and, most importantly, it exceeds the width of the corona by at least 2 orders of magnitude. This reaffirms the validity of our previous conclusions that decohering effects are negligible.

Another decoherence factor could be the dust near the corona, which plays a crucial role in the F region. The process of interest is the scattering of photons off dust particles, which largely depends on their size. Fragments smaller than 1 μm are not expected near the corona since they are pushed away by radiation pressure and electromagnetic forces [15]. For this reason, the brightness of the F corona, mostly of a thermal nature, is dominated by the near–IR range of the electromagnetic spectrum [16]. For radiation of shorter wavelengths, one can compute $\ell = (\sigma_{\mathrm{geom}} n)^{-1}$, where σ_{geom} is the geometric cross section of the dust particles. The average flux detected by Helios [17] in a range of heliocentric distance from 0.3 to 1.0 A.U. was of $(2.6 \pm 0.3) \times 10^{-6}\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}$, with dust particles of size 0.37 μm. Taking the worst case scenario, the flux at the photosphere is

$$\Phi = 2.6 \times 10^{-6} \left(\frac{1\ \mathrm{A.U.}}{R_\odot}\right)^2 \mathrm{m}^{-2}\,\mathrm{s}^{-1} \approx 0.12\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}, \tag{11}$$

corresponding to an interaction rate $\Gamma = \Phi \sigma_{\mathrm{geom}} \simeq 5.16 \times 10^{-14}\ \mathrm{s}^{-1}$ and a MFP of 6×10^{21} m. Similarly, the Solar orbiter estimated a flux of $8 \times 10^{-5}\ \mathrm{m}^{-2}\,\mathrm{s}^{-1}$ at 1 A.U. for particles of size of order 0.1 μm [18]. A similar calculation leads to an interaction rate of $10^{-13}\ \mathrm{s}^{-1}$, and a MFP of order 10^{21} m, the same as our previous estimate.

As large as these MFPs are, they are relatively short in comparison to those associated to interactions with the blackbody radiation from the photosphere, where $\ell \sim 10^{43}$ m. This is due to the weakness of the interaction, with the cross-section dependence as $\alpha^4 \sim 137^{-4}$.

One potential decohering effect that cannot be assessed through direct particle interactions is Faraday rotation. To evaluate the impact of the Faraday effect, we can estimate the rotation measure angle β, which quantifies the effect for a given wavelength λ. It is given by the expression

$$\beta = \frac{e^3}{8\pi^2 \epsilon_0 m^2 c^3} \lambda^2 \int_{R_\odot}^{d} n_e(s) B_\parallel(s) \mathrm{d}s,$$

where $n_e(s)$ represents the electron density in the medium and $B_\parallel(s)$ denotes the component of the magnetic field along the trajectory [19]. For an upper bound approximation, we can utilize Eqs. (7) and (8), together with the assumption of $B_\parallel \sim 100\ \mu\mathrm{T}$, which is an exaggerated approximation for the entire spatial range under consideration [20]. This simplified calculation yields

$$\beta(\lambda = 100\ \mathrm{nm}) \simeq 10^{-18}.$$

Hence, the overall effect of Faraday rotation on the state is exceedingly small and would impact every photon uniformly. This is due to the expectation that the photons are part of the same wave train, with a microscopic separation, whereas the coherence lengths of the magnetic fields involved are macroscopic. Consequently, this effect leads to an overall rotation without any decoherence effects.

Another effect, birefringence, though typically addressed in terms of the wave properties of photons, ultimately still arises from the collective interactions of the photons with the particles in the medium. The particle analysis we conducted already accounts for these interactions, rendering long MFPs. While our analysis employed the Thomson scattering formula instead of the more intricate Klein-Nishina expression, our conclusions are highly robust, because the Thomson cross section is always larger than the Klein-Nishina one. As a result, we can confidently extrapolate our findings to higher dispersion energies. This assertion applies equally to the Faraday effect, as far as decoherence goes. Thus, the lack of interactions from a particle perspective results in an effective transparency from a wave point of view. Finally, it is important to note that the occurrence of the Faraday effect does not necessarily imply decoherence of the state. Similar to our study on effects from gravity [2], it suggests a change in fidelity, which should be distinguished from the loss of quantum coherence, a crucial differentiation for our specific objectives.

Other potential decoherence factors have been discussed elsewhere [1,2,21]. There, it was found that photons at the energy ranges discussed here would not interact with the cosmological medium, or the cosmic background of photons in the microwave, IR, and x-ray bands, with other interactions depending on the particular local environments the photon travels through. For example, x-ray photons could travel through the interstellar medium without interacting with other particles for distances up to 1 Mpc depending on the region, although this can be reduced to 100 pc for dense HII regions. Factors like the matter environment of the Solar System have also been considered, yielding almost null probabilities of interactions.

Finally, it is worth noting that the quantum nature of a photon state is also unaffected by gravity (see [2] and references therein). The effects of gravity on quantum states have been extensively explored in the literature, especially in the context of quantum communications and the potential applications stemming from them. Some examples include the effects of gravity on quantum information protocols [22], frequency spectrum deformation [23], gravitational distortion of quantum communication [24,25], geometric phase acquired as a wave packet travels over a null geodesic [26,27], and gravitational redshift induced transformations on the photon state [28,29]. In the context of this work, it is crucial to recognize that while the photon state may experience changes affecting features like the fidelity in quantum communications, its fundamental quantum nature remains unaltered. As a result, in the case of the N-identical photons states discussed in this paper, any phase effects induced by gravity will be uniform among all photons within that state, ensuring the preservation of their quantum integrity up to an overall phase. Consequently, even though our analysis primarily focuses on the solar corona, it is plausible that signals originating from other stars can also reach our detectors near Earth essentially intact, especially in the UV and x-ray range.

VI. MEASUREMENTS

In principle, measuring the quantum nature of a signal from space could be significantly more challenging than in a controlled setup. However, one could potentially use the same principles that are common in Earth-based experiments. For one, direct measurements of the photons could be made through interference experiments that induce a phase between split signals leading to characteristic correlations depending on their nature. For example, the Hong-Ou-Mandel effect [30] could be used to test the indistinguishability of the two photons. The effect occurs when two identical single photons enter a 1∶1 beam splitter through different input gates, and under certain temporal conditions, the two photons will always exit the beam splitter together through the same terminal. This effect has been used in an astrophysical experiment by Deng *et al.* [31,32] for testing quantum interference between single optical photons from the Sun and a quantum dot on the Earth, to provide distinct evidence for the quantum nature of thermal light. Other astrophysical quantum experiments in the optical region have also been proposed by Dravins *et al.* [33,34]. Our above analysis has shown to minimize environmental decoherence, the UV and x-ray are good regions for testing our proposed mechanism. Alternatively, indirect measurements could be made through examining the distribution probability of thermal signals, which would defer from that of quantum signals. For example, the states emitted by a laser follow Poisson statistics, where the probability of measuring N photons in a given coherent state peaks significantly around the mean value. On the contrary, for thermal sources the largest probability always corresponds to the no-photon state, with the distribution function decreasing less rapidly than for coherent states. Thus, provided that detection at the photon level can be performed, current technology is well suited to discern a quantum signal from a classical one, but extending into the UV and x-ray bands and to our particular type of N-identical photons states still needs further development.

VII. CONCLUSION

This work has identified the emission of specific types of quantum states of photons, N-identical photons states, originating from specific processes, stimulated emission, in the atmosphere of stars. Focusing on the Sun, we showed that arriving at a $1-\mathrm{m}^2$ detecting region near the Earth the rate of such N-identical photons states would be a few per second and thus should be measurable. An actual experiment could of course be done at a distance closer to the Sun, which would increase signal flux and reduce residual decoherence and some possible experimental errors. We also showed such states would not undergo decoherence both leaving the solar environment and propagating from the Sun to Earth, especially in the UV and x-ray regions. From our previous work [1,2,21], we expect that such states can also arrive without decoherence from stars at interstellar distances away.

It is remarkable how the creation of such quantum states can be specifically identified within an astrophysical body and that such states then can traverse astronomical distances without decohereing. In fundamental terms this work has extended the distance of measurable quantum phenomenon, and that at the individual particle level, to astronomical scales. In practical terms these results provide a new probe for studying stellar atmospheres.

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