THE PHYSICS OF THE SODIUM LASER GUIDE STAR: PREDICTING AND ENHANCING THE PHOTON RETURNS

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ABSTRACT

Not all lasers give the same photon return/watt and it is this parameter, rather than the raw power generated by the laser, that is the more important figure of merit. In this paper we outline the physical processes involved in calculating this photon return from different types of laser, starting off with the single frequency CW laser developed at the SOR facility. Methods of increasing the return are then discussed and recent experimental results from chirping experiments at Palomar Observatory presented.

1. INCREASING THE COLUMN DENSITY OF SODIUM ATOMS IN THE MESOSPHERE

About 100 tons of meteorite burn up in the upper atmosphere every day, producing of about 100 kg of sodium metal [1]. The metal is removed by various complex physical and chemical processes, which ionize the atoms at high altitudes and lock the sodium atoms either into chemicals or on the surface of sub-micron sized "smoke" at altitudes below 85 km [1]. The total mass of sodium available in the entire mesosphere for generating a guide star is about 500 kg, implying a lifetime of about 5 days, with significant annual and diurnal variation. Greatly enhanced short-lived sodium abundances , so-called "sporadic" sodium , occur on shorter time scales which can increase the abundance by over a factor of ten for periods of minutes to hours [2]. Typical column densities are between 2 and 7 x 10^{13} atoms/m^2 with peak densities sometimes exceeded 20 x 10^{13} atoms/m^2 [2]. It is remarkable that so little sodium metal can backscatter even a few per cent of the radiation from a laser beam and it is conceivable that a few tens of kg of sodium metal, suitability dispersed, could greatly increase the brightness of the LGS locally but for periods of hours. Should such a technology prove feasible, the use of potassium metal, which occurs at a favorable wavelength for laser technology and could allow two-frequency LGS AO, might be even more effective. Such a strategy would be expensive but might of value for important transient targets. In the meantime the only way to increase the return is to build either more powerful lasers or improve the efficiency of producing photons from the sodium atoms.

2. OPTICAL PUMPING IN THE SODIUM ATOM

It is well known [5] that, for the D_2 line used to produce laser guide stars, the sodium atom has two ground levels, an upper F=2 state and a lower F = 1 state, with 5/8 of the atoms being in the F=2 state under conditions of thermal equilibrium. The upper F levels is split into 4 hyperfine sublevels each separted by some tens of MHz. All levels are additionally divided into different M levels, which have the same energy but different cross-sections to the radiation field. A simplified energy diagram of the atom is shown in figure 1.

If right handed circularly polarized photon of the appropriate frequency excites a sodium atom in the (2,M) ground state to the upper (3,M+1) level, it can decay to the (2,M), (2,M+1) or (2,M+2) ground level. If this is repeated and in the absence of other effects, the atom will then be optical pumped into a stable transition between the (2,2) and (3,3) state after a small number of cycles. Since this transition has the highest cross-section to the radiation field and highest backscattering efficency to ground, this optical pumping mechanism is very useful in increasing the photo return. We should note that the enhanced return is not only because of the enhanced backscatter return for this transition (a factor of 1.5 compared to isotropic scattering) but also because the cross-section is a factor of about 2 higher than the cross-section averaged over all M levels. We expect an increase in photon return of a factor of about 3 and this has been observed at MIT/Lincoln Labs with a suitably tailored laser spectral format and a well resolved spot [3].

However, we can also see from figure 1 that the photon return can be significantly reduced by depopulation of the F=2 ground state by another optical pumping process as follows. If the sodium atom is moving in slightly different direction, the energy diagram may favor transitions from the F =2 ground state to either the F=1 or F=2 upper state. For these excited atoms there is now a choice of ground state; an atom starting in the same ground (2,0) level may get excited to the upper (2,1) or even the (1,1) level and on decay may go either to the original F=2 ground state or the F=1 ground state. Because the energy separation between the two ground states (1.77 GHz) is substantially larger than the Doppler linewidth (500MHz HWHM), an atom pumped to the F=1 state will have minimal photon interaction with a single frequency laser tuned to pump atoms in the F=2 ground level and the photon return will be correspondingly reduced. There are thus two competing optical pumping processes at work, one pumping the atom to a favorable and stable (2,2) to (3,3) transition and one pumping atoms depopulating the upper ground state so that they no longer interact with a single frequency laser beam.

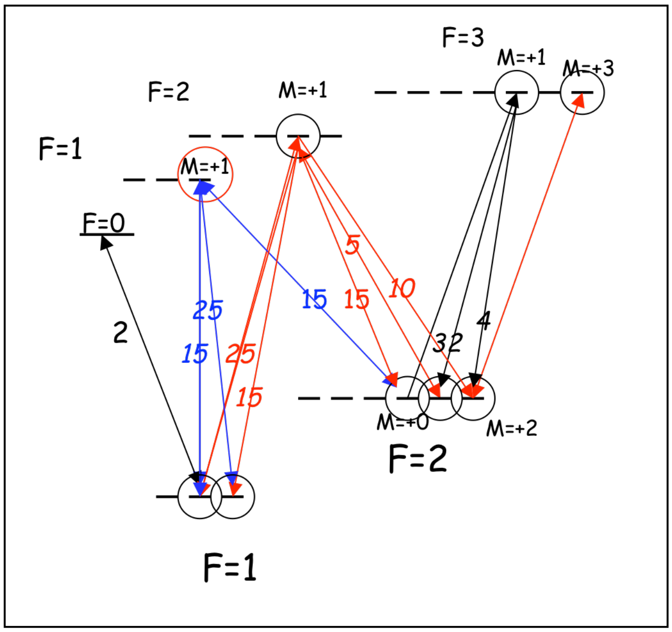

Figure 1: Simplified energy diagram of the Sodium D_2 transitions. The two ground states are separated by 1.771 GHz.

3. INTERACTION OF THE SODIUM ATOM WITH ITS ENVIRONMENT

Other physical processes are also important and the environment of the mesosphere plays a critical role in the laser-atomic interactions. Firstly, the natural linewidth of the D_2 line is only 10 MHz FWHM, which is much narrower than the Doppler width of 1 GHz for atoms at temperature of 200^oK. This is shown in figure 2

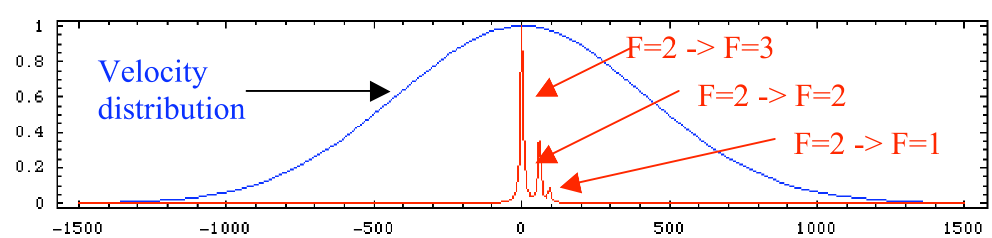

Figure 2: Doppler line of sight velocity distribution of sodium atoms in the mesosphere compared to the natural line width of the sodium D_2 line

Let us assume that that a single frequency CW laser is tuned to the zero velocity frequency of the F=2 to F=3 transition of the D_2 line. Because the natural line-width is so narrow, only a few per cent of the atoms, moving in a direction approximately orthogonal to the laser beam, have a strong interaction with the radiation field. An atom with a zero line of sight velocity will absorb and spontaneously reemit one photon every 170 nsec for a laser beam intensity of 10 watts/m^2 and will continue to reemit photons until it collides with an air molecule. It will then usually move in different direction and only minimally interact with the radiation field, until it finds itself again with another near-zero line of sight velocity after yet another collision. Sodium atoms in the mesosphere therefore emit photons in bursts when excited by a single frequency laser.

A sodium atom that has made either the transition to the upper F=1 or F=2 state has about an even chance of ending up in the lower F=1 ground level. Transitions to these upper F=1 and F=2 levels produce little extra light but enable substantial loss of atoms in the F=2 ground state to occur. It is important to realize that these transitions effect the total population of sodium atoms because even atoms moving in a direction hundreds of MHz from the laser line still have a small chance of interaction with the radiation field and, over a collision lifetime (100 µsec), can get pumped to the lower level - a cycle time of 50 µs is all that may be needed for a velocity class to be depopulated. This is shown in figure 3, which presents the number of atoms in the upper level as a function of Doppler velocity after a collision lifetime of 100 µsec. The laser has an intensity a 200 w/m^2, which typical for next generation LGS AO facilities. If there were no depopulation pumping, the curve would follow the conventional Doppler Gaussian curve, with a FWHM of about 1 GHz. Because of depopulation, a single frequency laser depopulates about 40% of the atoms in the upper ground state in100 µseconds (figure 3a). The situation is much worse for multi-line lasers, such as are used at the Gemini Observatory, essentially all the atoms being pumped to the lower level after 100 µseconds (figure 3b)

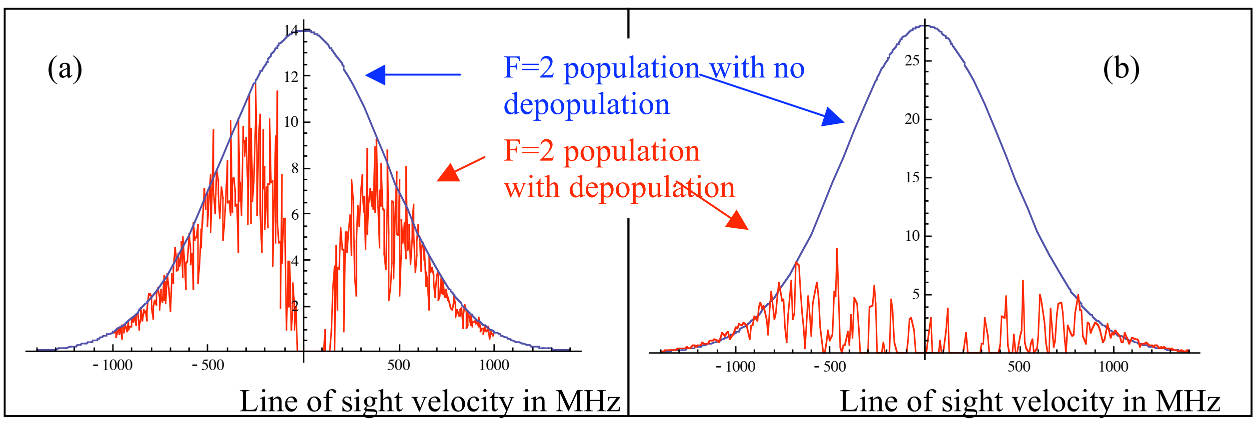

Figure 3: Population remaining in the F=2 ground state after a 100 µsecond collision lifetime for a laser intensity of 200 w/m^2. These figures include the effects of radiation pressure, Zenith pointing, 0.5 gauss magnetic field at an angle of 30^0 to the laser beam. (a) is for a single frequency CW laser (b) is for a laser with lines spaced 98 MHz apart under a Gaussian envelop of 800 MHz FWHM.

Spin Exchange

Collisions of sodium atoms with nitrogen molecules cannot bring the ground states back into thermal equilibrium. If this was the only mechanism for rethermalization we would be dependent on the flow of new atoms into the laser beam either by diffusion or mesospheric wind [5], both of which have typical time scales of a few milliseconds. This time scale should be compared to depopulation lifetime, which is similar to the collision lifetime (100 µs)
. Under these conditions the photon return would be quickly reduced to a fraction of its initial value. Fortunately there is another mechanism for repopulating the upper ground level available. The energy separation between the two ground states occurs because of relative spin alignments between the nucleus and electron, in the F=2 ground state the spins are parallel, in the F=1 state antiparallel. If the sodium atom has a close encounter with an oxygen atom or molecule the two particles can exchange electron spins and, after a small number of interactions, oxygen can pump the sodium ground back into thermal equilibrium whatever the initial population of the two ground states. The spin exchange cross-section is of the same order as the momentum transfer collision cross-section, so that we would expect spin exchange to occur about 1 collision with a air molecule in ten (20% of the molecules are oxygen

and half of these have spins opposite to that of the sodium atom, a condition needed to change spin). There are now two time scales at work, one defining the time between strong interactions of the sodium atom with the radiation field and the other being the time for the ground states to return to thermal equilibrium by interaction with oxygen. For a CW laser, the first time scale is of order the (Doppler width/Saturated line width), which is about 50 collisions, whereas the second timescale is fixed and is of order 10 to 30 collisions. The sodium atom is therefore able to experience a number of spin exchange interactions before it interacts significantly with the radiation field and we may therefore expect that, by then, the sodium atom population will be approximately rethermalized. However, a multiline CW laser that consists of a number of single frequencies spaced about 100 MHz apart will have more frequent, if less intense, interactions with the radiation field and therefore less time to rethermalize between interactions. While for this laser, the line width of the sodium atom will be somewhat less than that of a single frequency laser of similar power, the appropriate time between interactions will now be of order the (Mode Spacing/line width), or less than 10 hard sphere collisions. The sodium atom population will then not have time to rethermalize and there will be significant depopulation of the upper ground level. One reason for the significantly lower photon return of the LMCT laser compared to the SOR laser is due to this effect, there are just less sodium atoms available in the upper ground state to interact with the laser because of wide scale depopulation pumping in all velocity groups. This conclusion is not valid for a long pulse laser, such as the one in operation at Palomar. Although this laser has a similar spectral format, the time between pulses (a few msec) is more than sufficient to allow essentially complete rethermalization before the next pulse. For this type of pulsed laser we expect a similar photon return/watt to that of the single frequency CW laser and that both will have a significantly higher return than CW multiline lasers; this appears to be born out experimentally [4].

4. MODELING THE PHOTON RETURN FOR THE SINGLE FREQUENCY CW LASER

There are three more effects that must be incorporated into any realistic model of sodium atomic interactions, one is radiation pressure, another is the effect of the Earth's magnetic field and the third is the effect of near collisions between sodium and air molecules.

Radiation Pressure

Every time a sodium atom absorbs a photon there is momentum transfer in the direction of the laser beam and, on average, a net red shift of 50 kHz/photon absorption. Even if the sodium atom is initially moving in a direction giving the maximum return, the rate of photon production is reduced by a factor of 2 in 100 cycles. For single frequency line of intensity of 20 watt/$m^{2,}$ this occurs in about 10 μsec, so that radiation pressure significantly reduces the photon return, especially for the long collision times in the upper parts of the mesosphere. Because the mean collision time changes by a factor of over ten across the mesosphere it is not in general possible to consider an mean collision time, rather we must calculate the photon return as a function of height and sodium density and integrate the total photon return through the mesosphere.

Magnetic Field

Another effect is Larmor precession of the atom in the Earth's magnetic field. In the absence of a radiation field, Larmor precession shifts the M level state of the atom in a periodic manner so that an atom initially in the preferred (2,2) ground state will get shifted to a neighboring M level in a time scale of about 1 μsec, returning to its original level in about 6 μsec. If the atom is cycling in the radiation field at much higher rates than this, the atom will tend to remain in the (2,2) state and the return/watt will be high. If, however, the cycle time is much lower than 1 μsec, the M levels will tend to be scrambled and the photon return reduced because both the mean cross-section and backscattering efficiency are reduced. This is the other reason for the low return of the Gemini laser - a multi-line CW laser spreads its power between the lines so that while more sodium atoms are excited at any one time, basically because there are more lines available for interaction, the cycle time of atoms is increased and the effect of the Earth's magnetic field becomes more important.

Near-miss collision lifetime

Most calculations of the photon return from the mesosphere assume that collisions occur between hard spheres with radii derived from viscosity measurements. For this class of particles the scattering is isotropic and independent of the collision energy between particles. For momentum changing collisions, which are important for viscosity, the hard sphere and more advanced calculations using, for instance, the Lennard-Jones model, produce similar results. However for our case, a “near collision” in which the velocity of the sodium atom is changed by only a few percent in the orthogonal direction of its motion can totally change the interaction cross-section between the sodium atom and the light. Atmospheric molecules are neither hard nor spherical and long range interactions between the sodium atom and other molecules have a significant effect, especially because the intermolecular potential energy between nitrogen and sodium is substantially higher than the temperature of molecules in the mesosphere. The scattering angle as a function of reduced impact parameters is shown in figure 4 using a Lennard Jones model. These calculations only approximate the full quantum mechanical calculation, which should certainly be used for low scattering angles, but suggest that the near-miss collision cross-section, introducing a 5 MHz shift in the line of sight Doppler velocity, is over three times that given by the hard sphere model. This topic will be discussed in a later paper. We should note here that the more correct model is one in which the sodium atom makes small “random walks” with near misses and small velocity shifts in positive and negative directions until it experiences a significant direction changing collision. The effective collision time assuming this process appears to be about half that of the hard sphere scattering model. The collision lifetime is thus another difficult parameter to estimate and may require empirical determination from the data.

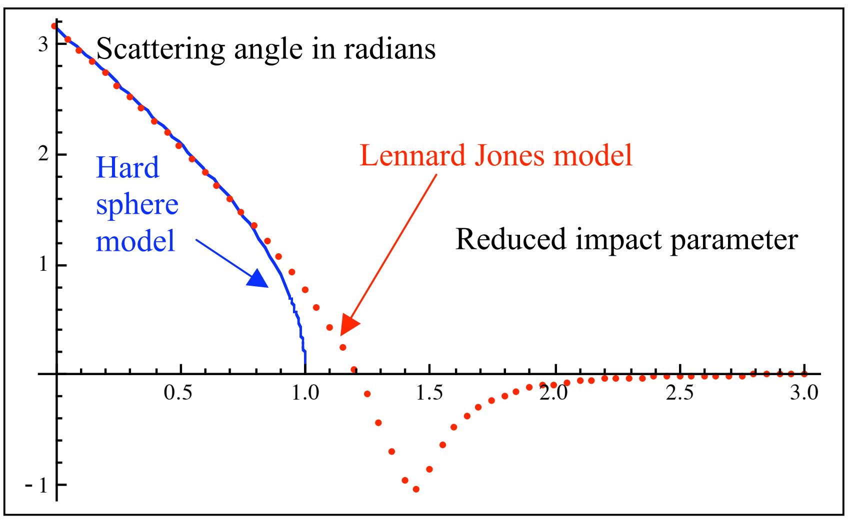

Figure 4: Scattering angle for Nitrogen and sodium interactions for Hard sphere and Lennard Jones interactions.

Monte Carlo Simulations

It is conventional to use Optical Bloch Equations (OBEs) to describe the atom, suitable modified to take account of magnetic fields, radiation pressure and collisions in order to calculated photon returns for the sodium atom. These calculations solve the time averaged photon return over the ensemble of sodium atoms but are opaque to non-experts (including the author) in the field and have some problems capturing the full physics of the interaction of the sodium atom with its environment. We have used instead a simpler Monte Carlo approach based on the use of rate equations. These rate equations give similar results to OBEs when the pulse length is long compared to the natural lifetime (16 nsec) [6] or, for short pulses, when the atom is not highly saturated [7]. Rate equations also do not model intralevel coherences within a level, but again these are small for conditions of interest [8] and they capture the other physical processes directly.

5. RESULTS FOR SINGLE FREQUENCY CW LASER

Saturation

One of the first results of the simulations was the effect of saturation on the photon return due to the finite lifetime of the sodium atom in the upper level. It is conventional to assume that the photon return/watt is reduced by a factor of two at a photon intensity level of 62.4 watts/m^2. However, this saturation intensity is only valid for the peak return (line center) of the (2,2) to (3,3) transition. At higher intensities linewidth increases by an amount equal to $\sqrt{1+\frac{I}{I_{sat}}}$ so that the total fraction of atoms in the Doppler velocity population that interact will the radiation field is also increased. This reduces the saturation of the photon return/watt. Photon return saturation effects are changed by radiation pressure and magnetic fields, the later because the saturation intensity level depends on the average cross-section of the atoms to the radiation field, which is reduced when the M levels in the ground state are changed by Larmor precession. Figure 5 shows that saturation of the line center and that of the photon return. The first has a saturation intensity of 62.4 watts/m^2 as expected, the second, the more important saturation parameter, is approximately 250 watts/m^2 for conditions at the Zenith at the SOR facility.

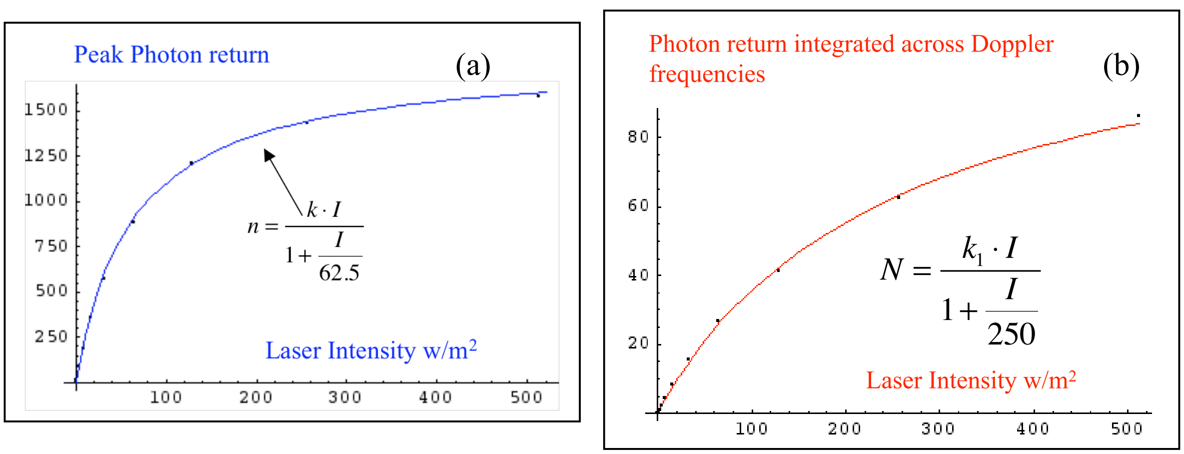

Figure 5: a. Saturation in the center of the D_2 line
b. Photon return as a function of laser intensity

Single Frequency CW returns

In figure 6 we show the predicts return for the SOR data in circular and linear polarized light using an earlier code which assumes a single collision lifetime chosen to fit the data. The best estimate of the collision time was 40 μseconds.

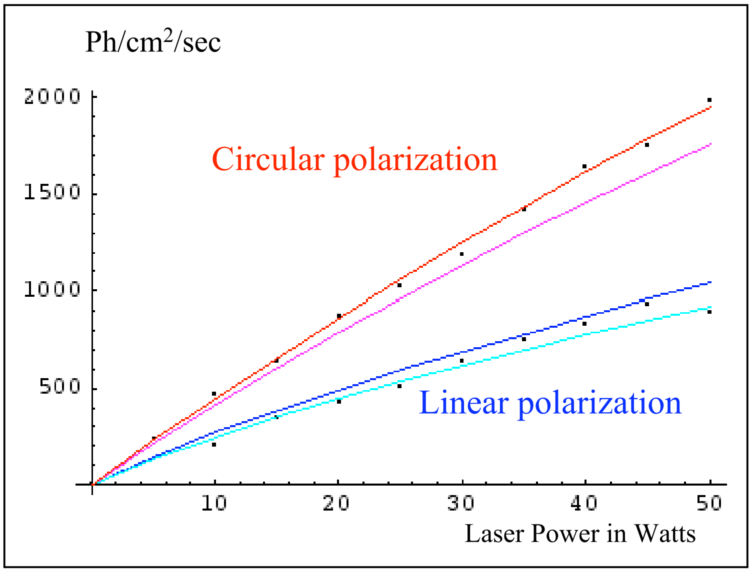

Figure 6: Calculated photon return on earth for the SOR laser assuming 2 arcsecond seeing and a column density of 1.9 x 10^{13} atoms/m^2. Collision lifetime is 40 μsec.

6. INCREASING THE PHOTON RETURN BY CHIRPING AND REPUMPING

Repumping

Tom Jeys and co-workers at MIT/Lincoln [9] proposed in the 1980s that if a second frequency, blue shifted 1.71 GHz from the primary frequency, were broadcast at the same time as the primary frequency, atoms originally depopulated from the upper ground level could be backpumped and used to repopulate this level. Steady state calculations on a single frequency CW laser were also carried out in Chicago in the early 1990's suggesting that, provided the laser intensity was sufficiently high, less than 10 per cent of the total intensity would be needed to repump the sodium atoms. The physical explanation of this is that once an atom has been pumped from the F=1 to F=2 ground state by the secondary frequency, it has a good chance of being pumped by the primary frequency into the (2,2) to (3,3) where it is relatively immune to depopulation provided the cycle time is much les than the Larmor precession time. Experiments recently carried out at SOR with two independent lasers have shown that improvements of over 60% in the return are possible using the second frequency [10].

Chirping

The second technique proposed by MIT/LL was chirping. This changes the frequency of the laser beam with time and uses radiation pressure to corral a velocity range of atoms that would not normally interact with the radiation field to be swept up into a red shifted velocity set by the chirp frequency. Theory predicts that chirping also only works successfully if the laser intensity is sufficiently high that the chirp rate is of ≥ 0.5 MHz/μsec - implying a cycle time of ≤ 100 nsec. Chirping can be readily implemented for the long pulse laser described in the next section.

7. CHIRPING EXPERIMENTS WITH A LONG PULSE LASER

Chicago/Palomar Laser

A long pulse laser based on the original MIL/LL design has been built at Palomar Observatory and has been in operation there for the last 4 years. This laser consists of two pulsed mode-locked Nd: YAG lasers operating at 1.06μm and 1.32 μm respectively that are combined in a LBO sum frequency converter. The laser generates long pulses (150 μsec), so that it is able to optically pump the atom towards its two level state. The pulse repetition rate of 400 Hz is long compared to the light transit time between earth and mesosphere and this allows the AO system to gate out backscattered light from the atmosphere and Cirrus clouds. The laser typical produces 8 to 10 watts of yellow light. Current returns are around 60-80 photons/sec/m^2 /watt [4];

The laser is the only long pulse laser currently in operation. It is simple to build and run. It has no closed loop control save for the temperature of the LBO non-crystals and operates in an dusty environment with no thermal control - the room temperature often changing from 50 to 80 ^{0}Fover the night. Even so, the laser has proved highly reliable in service, there have been no diode failures after over 2000 hours of operation nor nights lost due to laser failure. The laser has been modified for chirping experiments by placing one of the cavity fold mirrors on a piezo actuator driven sinusoidally and phase locked to the pulse frequency; the chirp rate can be changed by altering the drive voltage to the piezo actuator. The initial experiments were carried out in July 2009 and showed an 80% increase factor at a chirp rate of 0.6 MHz/μsecond. This enhancement was clearly visible on the acquisition CCD as the chirping was turned on and off. Additional experiments are planned in October 2009 that will include the ability to repump the sodium atoms using an EOLM modulator positioned in the 1.32 μm beam. The results of the initial chirping experiment are shown in figure 7; single points represent only one measurement at this chirp rate. Also shown is the theoretical return from our Monte Carlo calculations expected for simultaneous repump and chirp.

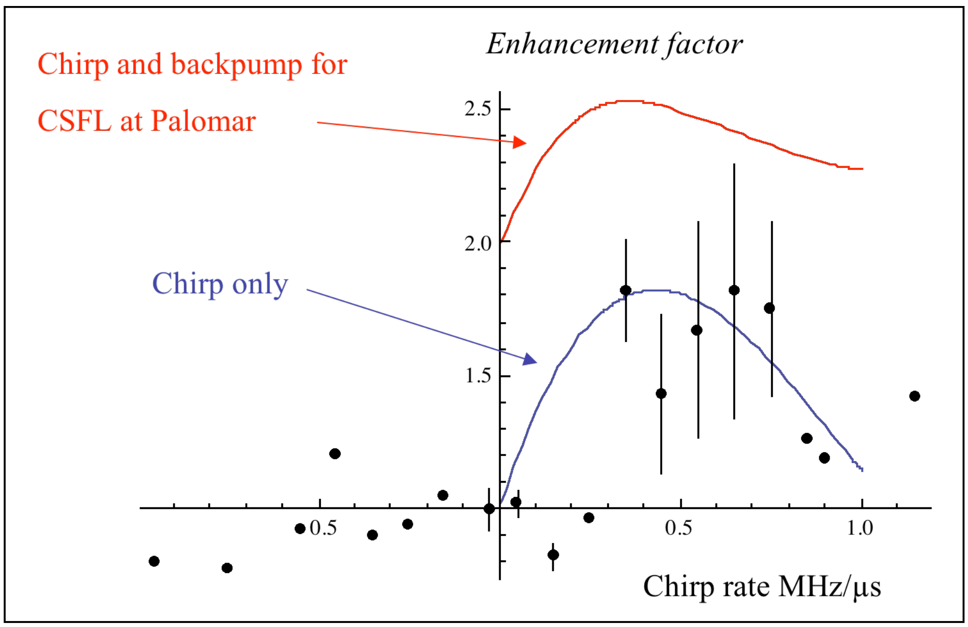

Figure 7: Photon return for initial Chirping experiment. Points record the relative increase in return compared to measurements taken before and after each new chirp rate. Points right of zero produce red-shifted chirps, points left red shifted. Solid curves represent theoretical returns for chirp (blue) and chirp+ repumping (red).

8. SUMMARY

We have described the basic physical processes that determine the photon return/watt from sodium in the mesosphere. High returns are generally associated with high pumping of the atoms, required to overcome the effect of the Earth's magnetic field; this favors single frequency CW lasers and long pulse multi-line lasers. Multiline CW lasers or lasers that have a significant continuous spectral broadening are not expected to have as high a photon return/watt. Implementation of the MIT/LL techniques of repumping and chirping appear to be able to increase the relative return of this laser formats by a factor of about 2.5.

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