Alternative guide stars for adaptive optics

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ABSTRACT

In addition to natural and laser guide stars for adaptive optics, it is proposed to use radio-created guide stars or fringes. Heating by intense radio beams either modulates sodium lamp illumination, or creates and modifies plasma in different altitudes. The plasma relaxes by artificial air glow, which is concentrated in few lines, mainly nitrogen and oxygen. Fringes between intense radio beams create plasma fringes, also visible from the telescope. Ionospheric heating was also shown to create patchy artificial aurora. In all cases, the multiplicity of sources or fringes allows multi-conjugate adaptive optics for wide fields of view, and shows promise for long base line optical interferometry.

Keywords: adaptive optics, artificial guide stars, atmospheric plasma, artificial air glow

1. LIMITATIONS OF CURRENT GUIDE STARS

Natural guide stars are few and far apart. They provide a scarce sky coverage, only doubled by the addition of asteroids[1]. Moreover, they allow only a limited field of view. Laser guide stars[2] also have a limited field of view, and suffer from the cone effect: subsampling of the atmosphere.

In trying to provide adaptive optical correction over wide fields of view it was proposed to use three or more sodium laser stars with the same number of wave front sensors[2]. The multiple paths allow tomography of the atmosphere and hence correction of two turbulence layers[3,4]. Unfortunately, stimulated sodium emission with laser power over 10W within a cross section of $1m^2$ limits the return signal. A solution to this problem was suggested by spreading an orthogonal grid of 2m fringes over a wide area of $2000m^2$. This approach[5] calls for a laser with power over 200W, and a single large wave front sensor. While both have been demonstrated, the global tilt error (even if smaller than with other schemes) might be a limiting factor. The tilt error can be resolved with polychromatic sodium lasers[6], which calls for two 200W lasers at two wave lengths.

While the idea of laser guide stars is not new, there seem to be some practical problems associated with them, not the least their availability and price, and their installation in the observatory: they require high power input and removal of excessive heat, and the beam needs to be transferred up, monitored and corrected. Safety issues also have to addressed, such as blocking of

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3. IONIZED ATMOSPHERIC REGIONS BY INTENSE RADIO BEAMS

Rather than modify the sodium-illuminated regime by affecting the local electrons, it might be easier to create plasma locally. Once plasma is created, electron scattering off the prevalent gases and their radiative relaxation will occur; this radiation can serve as a reference source for adaptive optics (Figure 2). It so turns out that this idea has already been studied many times and in detail for other purposes[9].

The first idea was to improve the reflection of radio waves behind the horizon by the creation of an artificial ionosphere[9-12]. In the simplest scheme, based on the Luxembourg effect, a radio beam heats up and ionizes or creates a break-down in the atmosphere, at an elevation of 30-60km. Efficient reflection of the distant radio waves occurs only at very high plasma density, so the idea was improved to have two radio beams interfere to create fringes. Radiation density culminates in the fringes where ionization starts, and the few electrons multiply very fast. The ionized fringes serve as a radio Bragg reflector, a more efficient scheme than mere return from a crude plasma volume[13,14].

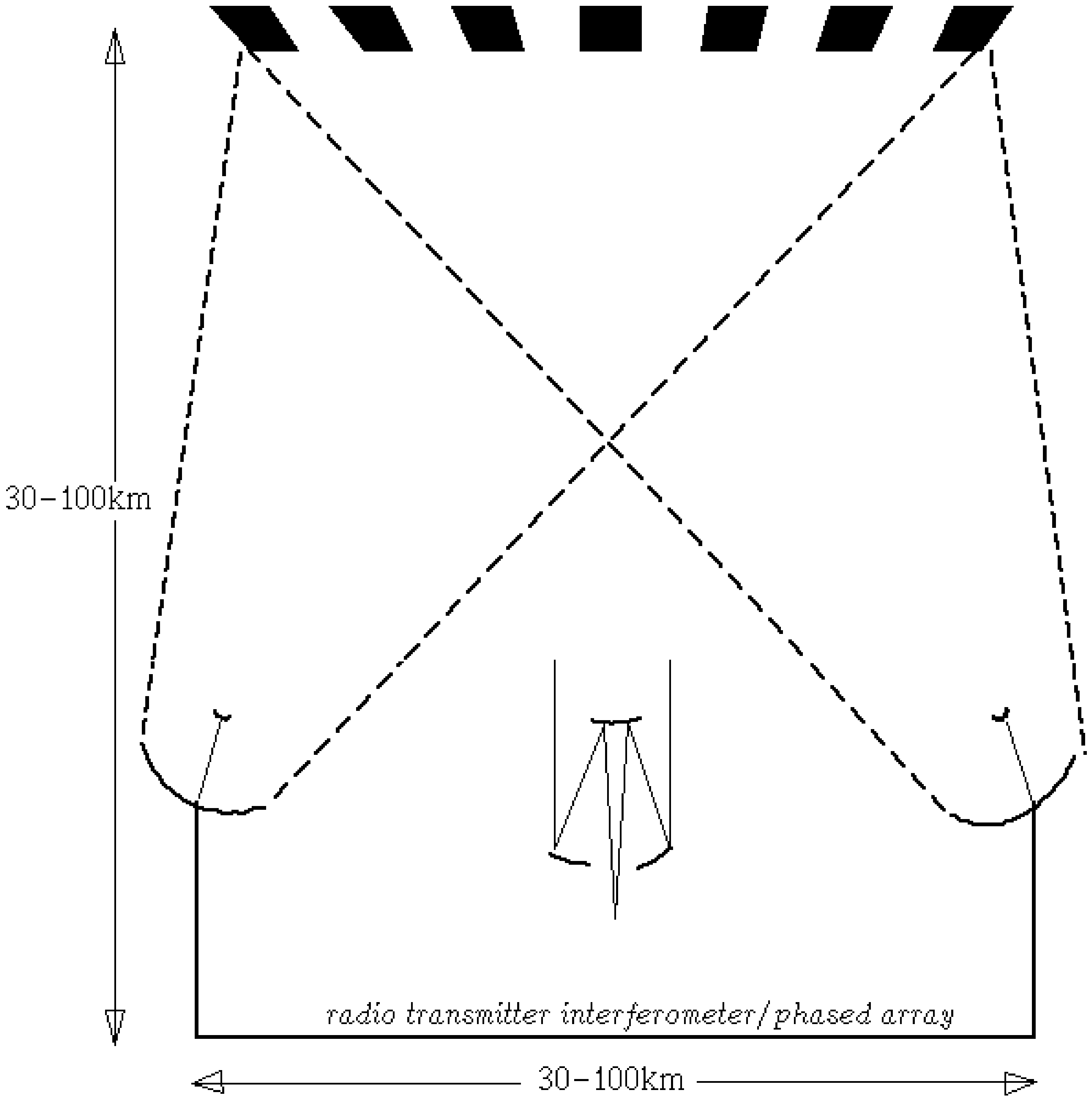

Figure 2: Radio breakdown of air in fringes. Air glow will appear in N3371Å, O5577Å, O6300Å, IR lines.

the beams before they hit aircraft or satellites.

Finally, the application of guide stars for long-baseline optical interferometry is important. A variant of the extended fringes[5] can be useful, but not all details are resolved as yet[7].

2. SODIUM LAMPS AND RADIO BEAMS

Alternatives to pumping of sodium atoms by tuned lasers can also be considered. For example, one can choose other atmospheric atoms or molecules. While sodium seems to have the highest efficiency, perhaps molecules would be easier to access in the infra-red regime, where lasers are easily available (e.g. CO_2 at 10.6 μm), and where wave front sensors become more efficient as time goes by. Let us turn our attention to other alternatives for illumination sources.

Incoherent illumination of the mesosphere by high-power street sodium lamps (as opposed to miniature sodium lamps[8]) is not efficient enough. When imaged at 95km the spots are too large and diffuse to lock on with a wave front sensor. However, these lamps are significantly less expensive than lasers, and their light might be used in a different manner: a large number of lamps illuminate an extended patch of the sodium layer, which can be on the scale of tens to hundreds of meters or even more. Onto this pattern one impresses finer interference fringes, created by radio waves. Transmitting from three or four distant radio dishes, or a phased array, the existing plasma is concentrated in the ridges of the fringes by the ponderomotive force and by local heating of the electrons (Figure 1). These enhancements can modify the scattering of light off the sodium atoms. It is not clear, however, that significant plasma density variations are created by the radio beams. If the effect is below a few percent, probably not much will be seen. It also requires to have many lamps and concentrators not far from the telescope, and a separate radio interferometer, with a rather complex infrastructure.

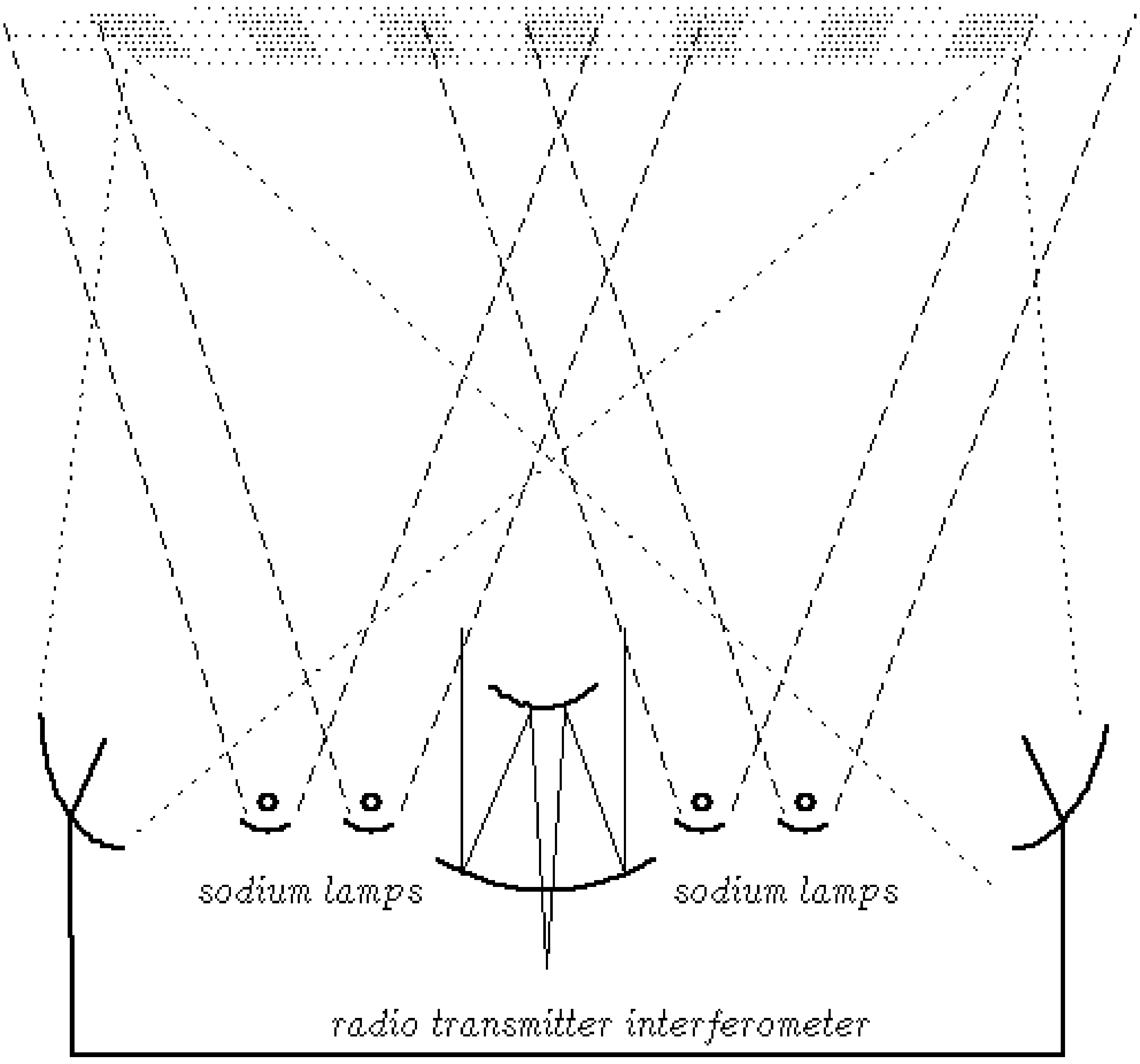

Figure 1: Illuminated sodium layer modulated by radio fringes heating of the plasma.

Gurevich[9] and others studied this problem in great depth. They were able to define the wave lengths of the radio transmitters as a function of elevation. In addition, they found out that using pulses to maintain the plasma was more efficient than a continuous wave, because radio absorption decreases as more plasma is created. Least power is required when the elevation is between 30 and 60 km. Most light is emitted in very few lines in the ultra-violet and visible regimes, by nitrogen and oxygen atoms.

The idea was also tested in the laboratory. As a tracer for the plasma fringes, the resultant artificial air glow was monitored, but no quantitative data are available for the number of emitted photons[15]. More experiments were apparently conducted in military laboratories both in the Soviet Union[16] and the United States[17].

4. ATMOSPHERIC LASERS

Artificial ionization was suggested as a means to study the aeronomy of the atmosphere, and as a means to create ozone above the south polar region, to replenish the recent depletion of this gas[9]. Another suggestion was to create a high power nitrogen laser (100kW inside $1m^2$) in the atmosphere, shining down on the ground[18]. Fringes are created between scanning microwave beams, with a crossing volume which travels down at the speed of light. The advancing breakdown regime is a source of first spontaneous and then stimulated emission (Figure 3). In laboratory tests 3KW radiation at 337.1nm were produced[16]. Utilization of this technology for adaptive optics will definitely require modifications in this scheme.

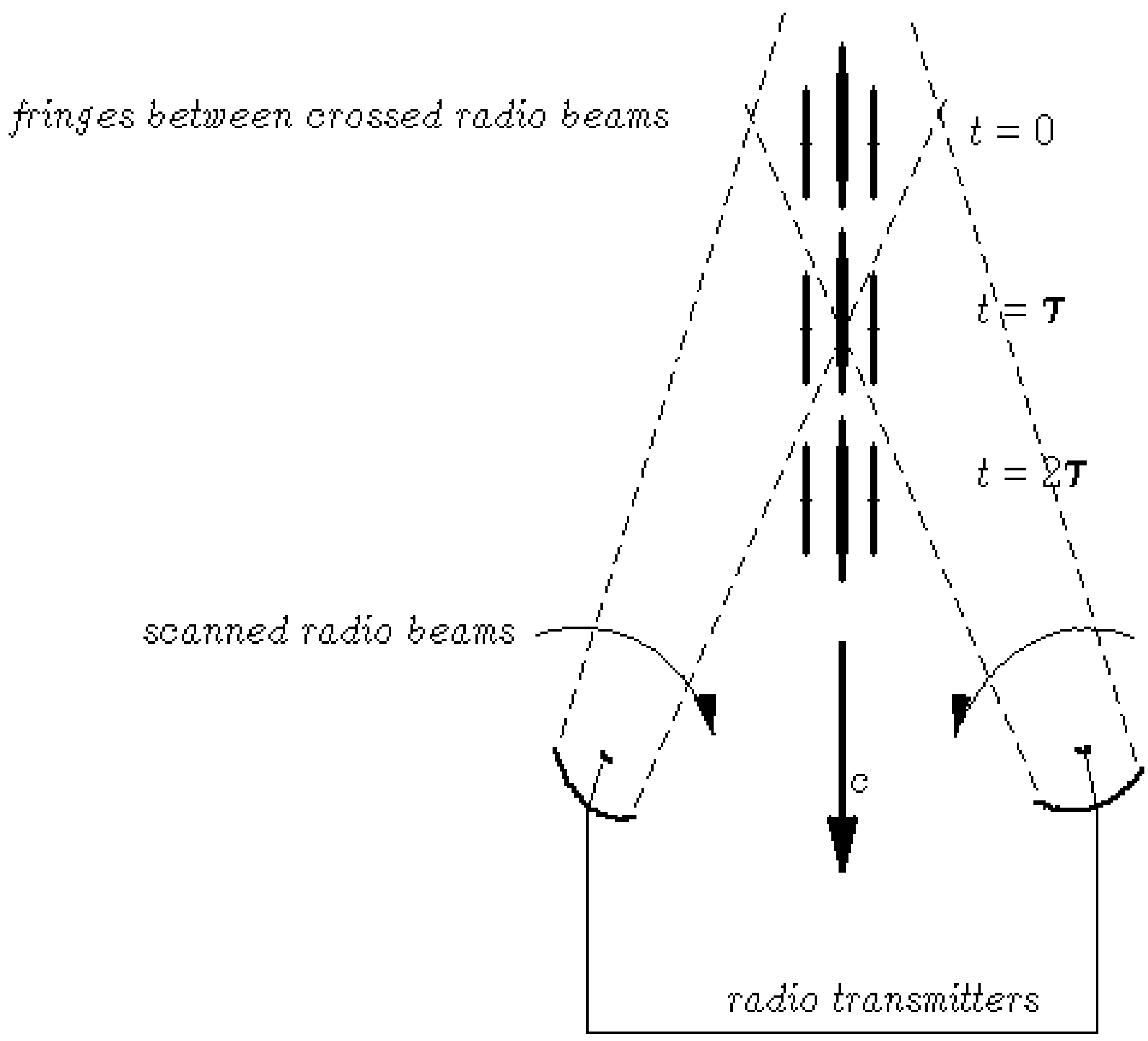

Figure 3: Nitrogen stimulated emission along travelling plasma wave.

5. HEATING OF THE IONOSPHERE

Plasma fringes between two radio beams are rather well defined when the atmosphere is dense enough and the wind velocity is low enough, so that diffusion is insignificant. As one probes the regions above 100 km conditions change. Here there are already enough free electrons to absorb the radio beam power efficiently, but the wind carries the heated patches away, and the rarefied medium around cannot keep the required shape of the fringes.

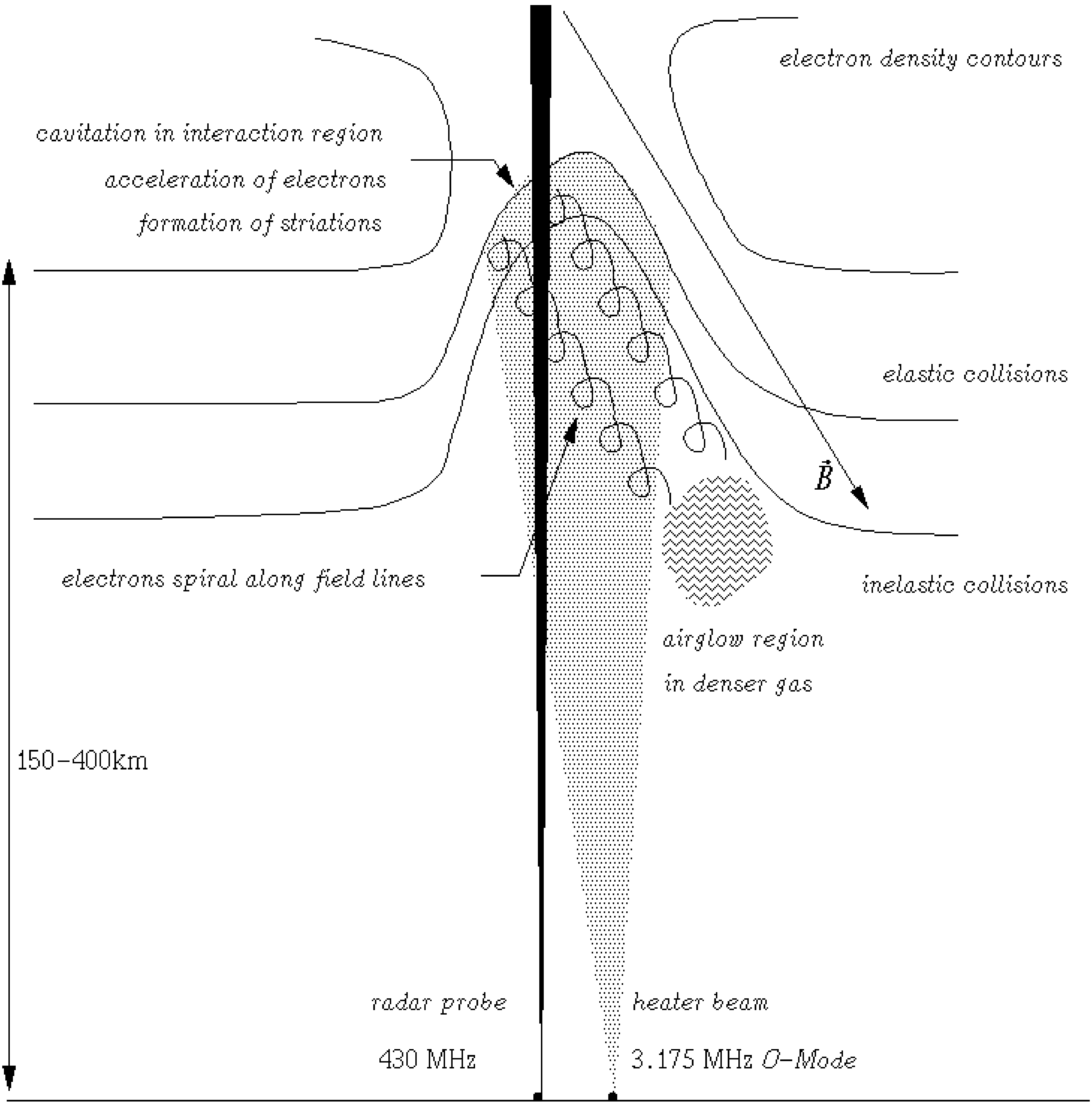

Figure 4: Ionospheric heating experiments (after ref. 22).

The ionosphere between 100 and 400 km was studied rather early on[19–23]. Radio heating of a large volume (typical dimensions were tens of kilometers) by a single radio dish, creates plasma and cavitation of the heated volume. The result is enhanced air glow, as well as a typical radio signature. Electrons ionized or accelerated in the heated regime spiral out of it along the earth's magnetic field. When they hit a volume with denser neutral elements, they create an illuminated regime. However, at these elevations the diffusion of the plasma and the fast winds disperse and shift swiftly any created pattern[22]. The electrons might be carried along thin striations which produce the airglow themselves[24]. In these experiments, relatively low power was required (10KW -2MW), in a continuous mode. Experiments carried out in Colorado, Arecibo, Norway and northern Russia all showed an artificial aurora[22,23] (Figure 4).

The ionospheric air glow is very patchy. This is due to the density variations of the excited volume. In addition, filamentation in the heated area was detected by radar. It is not clear what is the typical spatial frequency of the striations and what is their contrast[24]. Their average visible intensity is usually tens of Rayleighs (a Rayleigh is 10^6 photons/s cm^2 steradian), and values above 250 Rayleighs were also measured, i.e. brighter than 11^m/$arcsecond^2$. Natural night glow is around 60 Rayleigh, and is widely variable spatially and temporally.

6. APPLICATION TO ASTRONOMY

The choice of beacon elevation is important from the point of view of adaptive optics and interferometry: the higher the better, provided the pattern is stable enough and of high enough contrast on the few arcsecond scale. Above 200km the random pattern can still be used as a reference source, much in the same way that the solar surface serves for adaptive optics[25]. Below 100 km the density of the atmosphere is high enough that the plasma mean free path (a few cm) is much shorter than the required fringe period[5] (less than 2m). Thus the luminescent fringes follow the radio-heated ones. Experiments[15] show that the most efficient air breakdown occurs around 0.5-5 Torr, corresponding to an elevation of 30-80km. The sodium layer at 87-95km is also possible, but the prevalence of the OH hydroxyl at this elevation should be taken into account. On the one hand it could be a limiting factor, because of its air glow in the near infra-red. On the other hand it could still be considered as a part of the beacon. It might be that only the elevation of 100-120 km will be appropriate. It is not known whether striations, detected by radar at higher elevations, will also be visible as air glow at these heights. If so, their geometrical shape (2-5m along the magnetic field lines) could be an advantage.

Laser guide stars suffer from the problem of determination of the ascending beam global tilt, which is difficult to measure and remove from the descending beam. Radio beams also suffer from atmospheric turbulence, but it is now independent of the optical turbulence, and the beams trace very different paths. In addition, the few lines of the artificial air glow will allow differential measurement of their elevation[6]. Blocking of the Rayleigh scattering is another problem with sodium guide stars, which does not exist with radio beams.

The reference radiation can be distinguished from the stellar light either temporally or spectrally. If the plasma produces wide band radiation (when it is thick optically), it will be difficult to tell from the scientific object, unless it disappears within a fraction of a millisecond, before the turbulence had changed much. In that case, very short pulses can be shuttered off the astronomical camera or spectrometer.

If the radiation is in lines only, narrow band filters can be used to pick it up, as is done today to separate the beacon radiation (Rayleigh or sodium) from the star light. In atmospheric plasma, oxygen and nitrogen lines are common and useful, but other elements might be preferable: sodium and iron can be found in the mesosphere. The decision which line to choose might be affected by other considerations; it was also found out that the 557.7nm oxygen line responds instantly whereas the 630.0nm line is slower[25]. Not much is known about infra-red lines, but if not used as reference, they might interfere with astronomical targets at the same wavelengths.

Radio absorption is different for different atmospheric elevations at different frequencies. Once ionization starts, the created plasma reflects the radio beams, which cannot heat it any more. In this case it is possible to switch to pulsed radiation. The required power could be in the range of tens to hundreds of kilowatts and more (Table 1). The limitations of laser guide stars are also valid here: high power might be disruptive for aviation, and special measures need to be taken to prevent accidents. Moreover, radio pollution of nearby radio-astronomical observations has to be avoided by careful planning of wave lengths and transmitter locations.

The problem of infrastructure might be significant. At least three transmitter dishes[5] are required to create the necessary pattern. For a fringe frequency of decimeters to meters, and wave length of centimeters to meters, the dishes have to be decameters to kilometers away from the telescope. They have to be pointed, synchronized and operated from the observatory. A phased array can also be used, with similar requirements.

Finally, the application of radio guide stars for long base-line optical interferometry requires special considerations. The biggest advantage is having all beacons emanate from the same interferometer (be it laser or radio). If the beacon is in the ionosphere it is also much further off and hence easier to triangulate upon, but that should be weighted against lower uniformity and perhaps fewer photons.

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	few lasers or laser fringes	sodium lamps and radio modulation	mesospheric break down of air	mesospheric nitrogen laser	ionospheric enhancement of air glow
source	lasers or laser interferometer	sodium lamps and radio array	radio dishes or phased array	radio dishes or phased array	large radio dish(es)
beacon shape	spots or fringes	flat with fringes	fringes	wide laser	patterned air glow
elevation [km]	85–97	85–97	30–90	30–80	100–300
light	sodium	sodium	air glow	nitrogen	air glow
decay time [s]	10^{-6}	10^{-6}	10^{-6}	10^{-7}	$10^{-1}-10^{2}$
pulse time [s]	10^{-8}		10^{-8}	10^{-8}	
freq. [Hz]	10^{15}	10^{15} and 10^{9}	$10^{9}-10^{10}$	$10^{9}-10^{10}$	10^{7}
total/pulse power [W]	40 w/spots or 300 w/fringes	10^{5} lamps and 10^{5} radio	10^{5} 10^{9}	10^{5} 10^{9}	10^{5}
distance to telescope [m]	0–10	$0-10^{4}$ lamps 10^{5} dishes	10^{5}	10^{5}	$0-10^{4}$
hazards	laser blinding	radio i.f	radio i.f. NO_x creation	radio i.f NO_x creation	radio i.f.

Table 1: Artificial guide stars alternatives.

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