Optical astronomy using radio techniques: Imaging Capella with unprecedented resolution

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Radio astronomers fully vindicated the oft-quoted maxim that necessity is the mother of invention when they went about the task of imaging celestial radio sources. What may seem to be a trivial job in optics, e.g. imaging the sun on to a white screen and looking at the sunspots, would require a radio 'lens' or 'mirror' that is over 100 m wide. Likewise, a 10 km wide lens would be needed to form an image of Jupiter in microwave radiation. This is because electromagnetic waves bend around obstacles (the phenomenon of diffraction) and fail to come to an exact focus. This fuzziness increases with the wavelength of the radiation. Light waves, being a million times smaller than microwaves, can be 'tamed' by lenses that are a million time more compact than the sizes mentioned above. Faced with this immense problem, radio astronomers since the fifties have followed the Nobel prize winning lead of Martin Ryle at Cambridge. They build up their images using a collection of smaller antennas distributed over large areas. The signals from each pair of antennas are multiplied together and averaged in time, yielding a quantity called the correlation. The separation of the antennas expressed in multiples of the wavelength is called the spatial frequency. The set of correlations for various spatial frequencies are then fourier transformed (a mathematical operation that does a sort of book-keeping on the number of waves present in a pattern of signals). The resulting function gives the brightness distribution of the source, as a function of the angular position. The theorem connecting correlations in the wavefront, with brightness distribution on the source, is called the van Cittert–Zernike theorem and was developed for optics! Formally, this technique of imaging is called aperture synthesis.

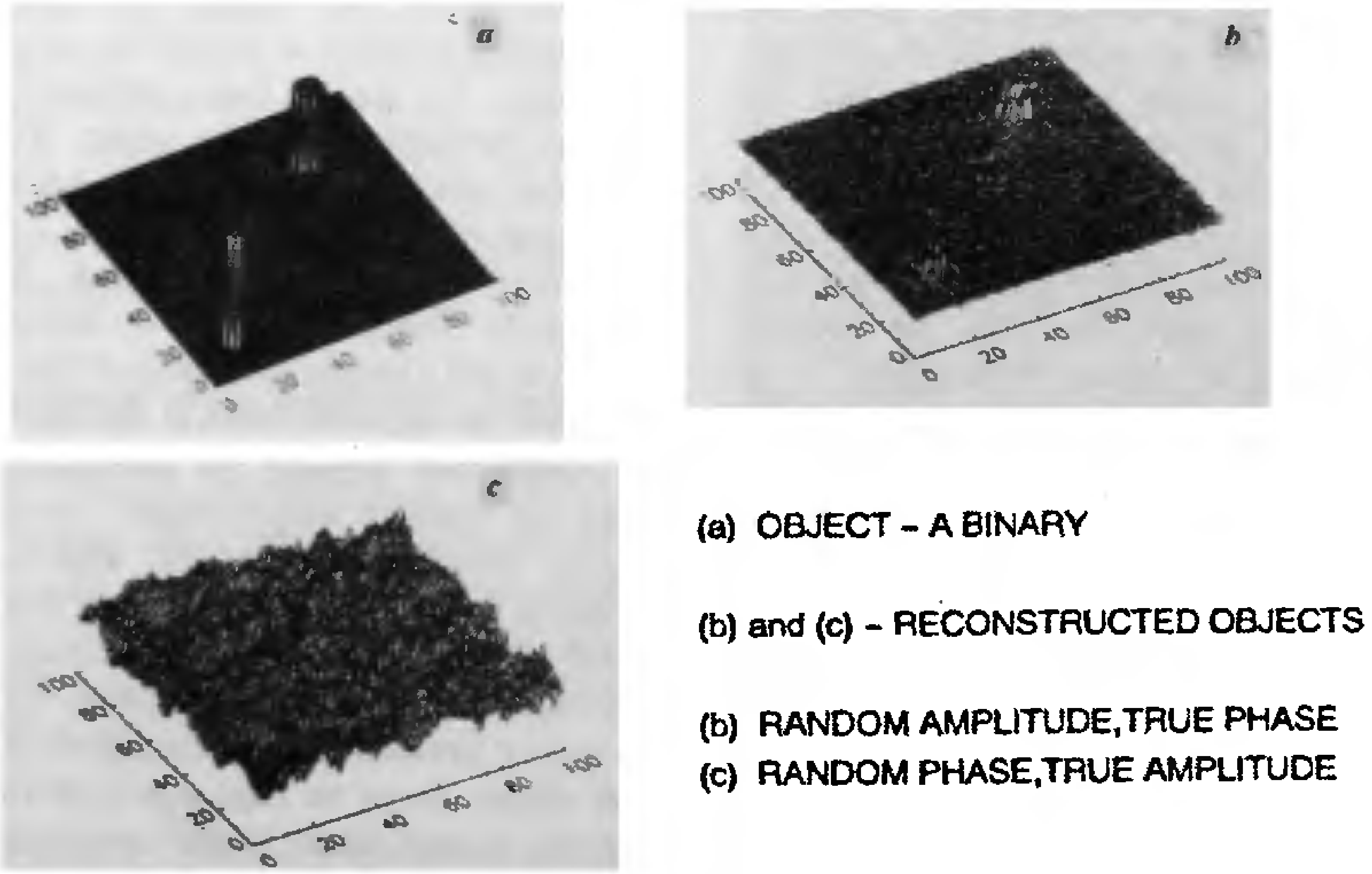
There is nothing in principle that prevents optical astronomers from using this technique (although it seems a somewhat round about way of imaging as compared to more conventional ways). The correlation is obtained by combining the beams from the two apertures and forming an interference pattern (as did the great optical physicist Michelson when he measured the diameter of some stars at the turn of the century). The larger the correlation, the deeper will be the modulation in the interference fringes. In practice, several factors inhibit the realization of this method. The path difference between the two apertures must be shorter than the longitudinal coherence length, otherwise the fringes will get washed out. This is the length occupied by that number of waves which is equal to the ratio $\lambda/\Delta\lambda$, which is the number of bandwidths present in one wavelength. For example, the coherence length is a mere 2.5 μm for a 100 nm bandwidth centered around 500 nm. The mechanical tolerance of the experimental setup is restricted to micrometre accuracies over the baselines (separations of antennas) that are used. If one wants to escape this constraint by using a very small bandwidth, then one will need to spend a lot of time to collect the required number of photons to achieve decent signal to noise ratios. However, the fluctuations in the atmosphere (that produce twinkling of starlight) allow only about 10 milliseconds to obtain the interference pattern. If one thinks that having large apertures would do the trick, then the spatial extent over which the standard deviation of the atmospheric fluctuations are within a reasonable limit (say, a quarter of the wavelength) is only 10 cm. Thus, having apertures larger than this limit does not help. So aperture synthesis at optical wavelengths is an extremely demanding enterprise and would interest the astronomers only if they need angular resolutions much beyond the diffraction limits of large single telescopes. A few groups of astronomers have been able to interfere light from two separated telescopes and use the depth of modulation of the fringes to resolve binary stars that are separated by a few hundredths of arcseconds. The prospect of producing a genuine interferometric image seemed bleak. But not anymore. For this feat has recently been achieved by John Baldwin and coworkers at Cambridge, UK (*Astronomy and Astrophysics*, 1996, 306, L13-L16).

The extra requirement to form an image is the knowledge of the fourier phase of the target source. The fourier transform of a symmetrical object is a real function which comes with a plus or minus sign. Asymmetric objects yield complex fourier transforms needing a phase angle anywhere between 0 and 360 degrees for full specification. The fourier phase (or visibility phase) is then the argument of the complex fourier transform. The modulus of the transform is called the fourier amplitude, or visibility amplitude. It represents the contrast of variations in the object at the given spatial frequency. The phase represents the morphology, or positional information of the variations at that spatial frequency. For example, an unresolved object at the centre of the field would continue to have undiminished visibility amplitude of unity at the largest separation of the antennas (or telescopes), corresponding to the largest spatial frequency. The phase would be zero degrees all through. A resolved object would have an amplitude that goes to zero at a spatial frequency corresponding to the inverse of the angular size of the source, while the phase switches from 0 degrees to 180 degrees at this spatial frequency. Knowledge of phase is crucial for imaging, since it provides basic information on the morphology of the object. For example, when the fourier amplitudes of a binary source (shown in Figure 1 *a*) are randomized, while retaining the phases, the object in Figure 1 *b* is obtained which is still a binary, albeit with different contrast. On the other hand, if the phases are randomized, keeping the amplitudes intact, the resulting image (Figure 1 *c*) is scarcely recognizable. Actually, what is needed is the relative phase between two spatial frequencies. Because of turbulence, it is impossible to 'freeze' one phase. So we require simultaneous measurements of three phases, hence we need at least three antennas or telescopes. If the turbulence introduces a random phase in antenna 2, it has opposite effects on baselines 12 and 23. The sum of phases on 12, 23 and 31 – the so-called closure phase, is thus an intrinsic property of the object with random properties of the medium cancelling out.

The COAST (Cambridge Optical Aperture Synthesis Telescope) instrument developed by John Baldwin and his group has four telescopes, of which three were used to image the star Capella. These telescopes are simple in design. The object is tracked by siderostats (flat mirrors rotating about an axis parallel to earth's rotation axis and inclined suitably to send the reflected beam along a fixed direction). These siderostats feed horizontal telescopes. This design has the great advantage that long moving parts are avoided, thereby achieving the stringent limits of mechanical accuracy set by the longitudinal coherence length. Light from each telescope is brought along evacuated pipes into a thermally insulated interference station (actually a grass covered bunker!). Pupil plane interferometry is employed rather than interference in the image plane. The advantage is that the width of the fringes can be controlled independent of the focal length of the imaging system. This is particularly useful for photon starved observations. In the COAST setup, the images of the interfering pupils are kept parallel, so that there is uniform illumination at the interfering plane. The interference is then detected by introducing a periodic path delay of about 50 µm sweep in each arm to produce a corresponding modulation in the combined light. This modulation is detected by an avalanche photodiode operating as a photon counter. The beauty of the arrangement is in the modulation of the fringe pattern of each pair of telescopes with a distinct periodicity, viz. 238, 477 and 715 Hz respectively. So, a single detector can record all the fringe visibilities, which are encoded in distinct temporal frequencies. The triple product of the three complex visibilities, corresponding to the three baselines can thus be conveniently recorded. The argument of the resulting complex number is the closure phase. Once the closure phase is known, the radio astronomers know how to reconstruct images from the visibility amplitudes and closure phases of a set of sparsely distributed baselines. The COAST experiment used interspersed observations of a single star to calibrate the visibility amplitudes.

Because of incomplete coverage in the spatial frequency domain, the reconstructed images will have many 'side lobes', which are carefully removed by an algorithm called CLEAN, which is very popular among radio astronomers. The projections of the three telescopes on to the sky plane move around with the rotation of the earth and a nice spatial frequency coverage can be obtained in this way. Two images of Capella were obtained for two epochs separated by 15 days. The relative positions of the components lie on an orbit agreeing with that predicted by other measurements. The separation of the binary is in the region of 50 milliarcseconds, while the position angle changed by about 50 degrees during the 15 day interval (see Figure 2).

Apart from the fact that this is the first genuine optical interferometric imaging of a celestial object with separated telescopes, it also provides an exciting peek into the future of optical astronomy. Conventional astronomers seek to build larger and larger telescopes to look at very faint objects. Eventually, when the mechanical problems of large telescopes become unsurmountable, they will have to fall back upon the concept of telescope arrays which Antoine Labeyrie, John Davis, Michael Shao, John Baldwin and their ilk have courageously tried to advance. Of course, it has not been easy for the COAST group (see *Physics Today*, April 1996, pp. 17–18). The project meth-



(a) OBJECT - A BINARY

(b) and (c) - RECONSTRUCTED OBJECTS

(b) RANDOM AMPLITUDE,TRUE PHASE
(c) RANDOM PHASE,TRUE AMPLITUDE

Figure 1 *a–c.* This figure shows the importance of visibility phase. The object of Figure 1 *a* was fourier transformed. The fourier phases were first left untampered. The fourier amplitudes were replaced by random numbers, with total power being conserved in the fourier domain. The reconstructed image is shown in (*b*). Next the fourier amplitudes of the original object were retained while the fourier phases were replaced by random numbers. The result of reconstruction is shown in (*c*). (Generated by R. Sridharan, Indian Institute of Astrophysics.)

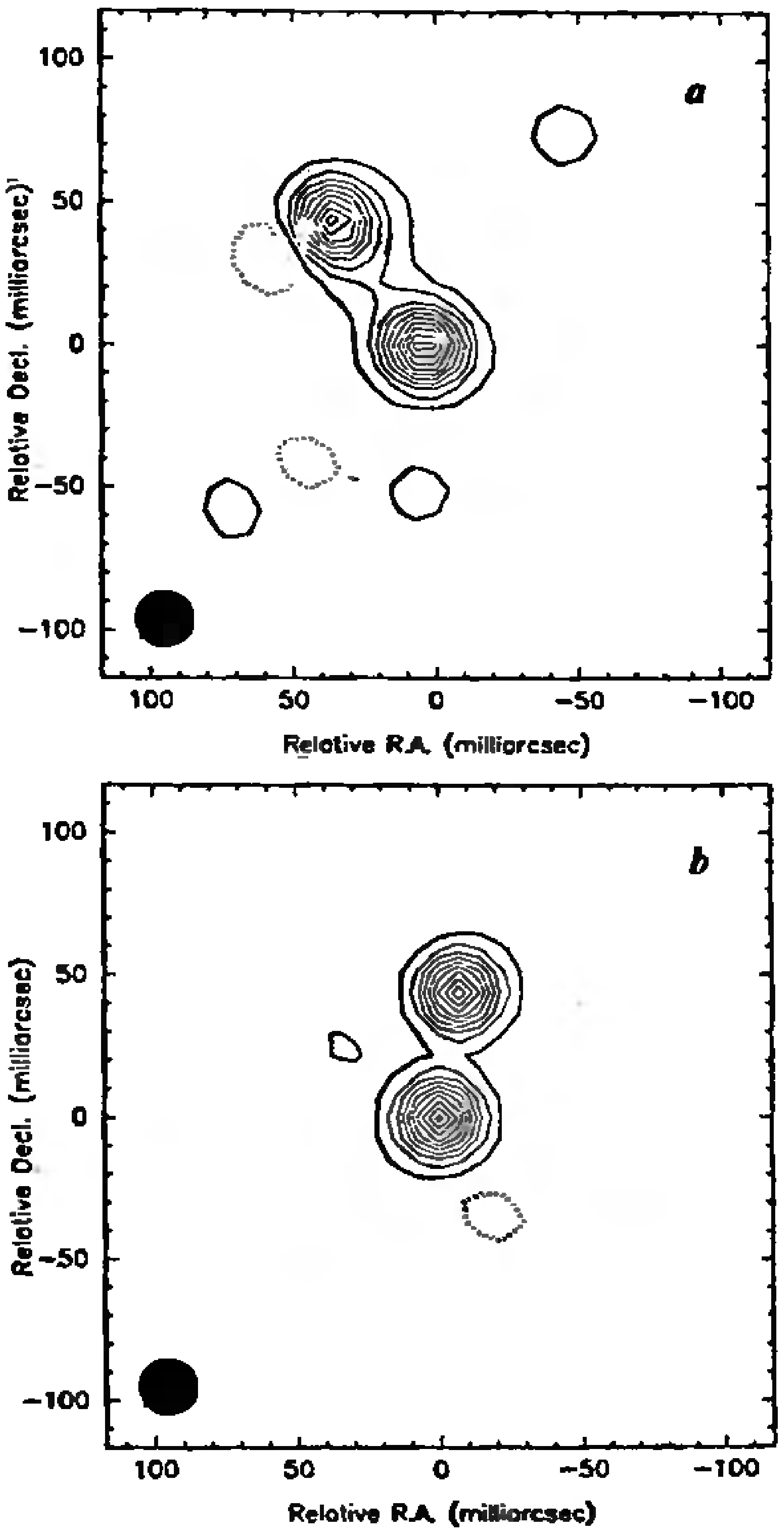


Figure 2. Image reconstruction of Capella from data obtained on the nights of the 13th (*a*) and 28th (*b*) September 1995. [Reproduced with permission from J. E. Baldwin *et al.*, *Astron. Astrophys.*, 1996, 306, L13–L16]

odology adopted by Baldwin is worth special attention, especially for younger persons embarking on new techniques. He started with experimenting on a few masks placed over a single telescope and gradually worked his way up to the current achievement. The paper which reported this achievement has a large number of authors from several institutions – a model for successful cooperation that merits special mention. We can expect several new discoveries when the sensitivity and resolution of this technique improve, and when the several other contenders in this game achieve similar successes.

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Volatile oil constituents and wilt resistance in cumin (*Cuminum cyminum* L.)

Cumin cultivation has received a serious threat from wilt disease which devastates the total standing crop. Screening of lines against cumin wilt under artificial/field conditions indicated that UC-198, UC-199 and RZ-19 have shown fairly good tolerance to wilt[1]. Different entries of cumin were evaluated for volatile oil contents and correlated with wilt incidence. To understand the role of volatile oil in disease resistance at the molecular level, the volatile oil was fractionated on GLC and correlation between volatile oil constituents and wilt resistance was determined.

Fourteen entries of cumin were grown at Agriculture Farm of S.K.N. College of Agriculture, Jobner under All India Coordinated Varietal trial. The volatile oil contents from these entries were evaluated using Clevenger apparatus[2]. The volatile oil was made moisture-free by using anhydrous sodium sulphate and stored in a glass vial. These samples were subjected to gas chromatographic examination as described earlier[3]. The identity of the constituents was ascertained by comparison of relative retention time with authentic standards. The percentage of oxygenated compound and hydrocarbons was recorded.

The negative correlation between volatile oil contents and wilt incidence (Figure 1) suggests that the variety with high volatile oil contents is less prone to wilt which was not true in all cases. The anti-microbial property of volatile oil was also reported by other workers[4,5]. Earlier we reported that the growth of wilt pathogen, *Fusarium oxysporum* was inhibited in presence of volatile oil of cumin. The effectiveness of inhibition varies from variety to variety[6]. To understand it at the molecular level, the main components of volatile oil of some varieties of cumin were determined. Volatile oil of cumin consists of a mixture of hydrocarbons (terpenes, sesquiterpenes, etc.) and oxygenated compounds (alcohols, ester, ether, aldehydes, ketones, lactones, phenols, etc.). Of these, the oxygenated compounds are the principal odour carriers, although the terpenes and sesquiterpenes too contribute to some degree to total odour and flavour. These components are separated on GLC on the basis of their partition coefficient. The hydrocarbon components and oxygenated compounds are having marked difference in the retention time due to polarity differences. The main constituents of volatile oil of cumin are cuminaldehyde, cuminyl alcohol, terpenes, p-cymenes, pinenes, etc. The first two components are oxygenated compounds and the last three are hydrocarbon compounds. So cumin oil has two types of

Table 1. Volatile oil constituents of cumin and relative wilt resistance

Entry	Volatile oil constituents (%) a	Volatile oil constituents (%) b	Ratio of a : b	Relative wilt resistance (0–9 scale)
UC-199	76	21	3.61	1-2 (R)
UC-198	55	38	1.44	1-2 (R)
UC-19 mnt	42	54	0.77	2–4 (MR)
UC-218	34	61	0.55	4-5 (MR)
RZ-19	30	67	0.44	4–5 (MR)
RS-1	30	68	0.44	7-8 (HS)
UC-208	28.4	71.5	0.397	4–6 (MR)
Local	16	82	0.19	9 (HS)

a = oxygenated components; b = hydrocarbon components. R = resistance; MR = moderately resistance; HS = highly susceptible.

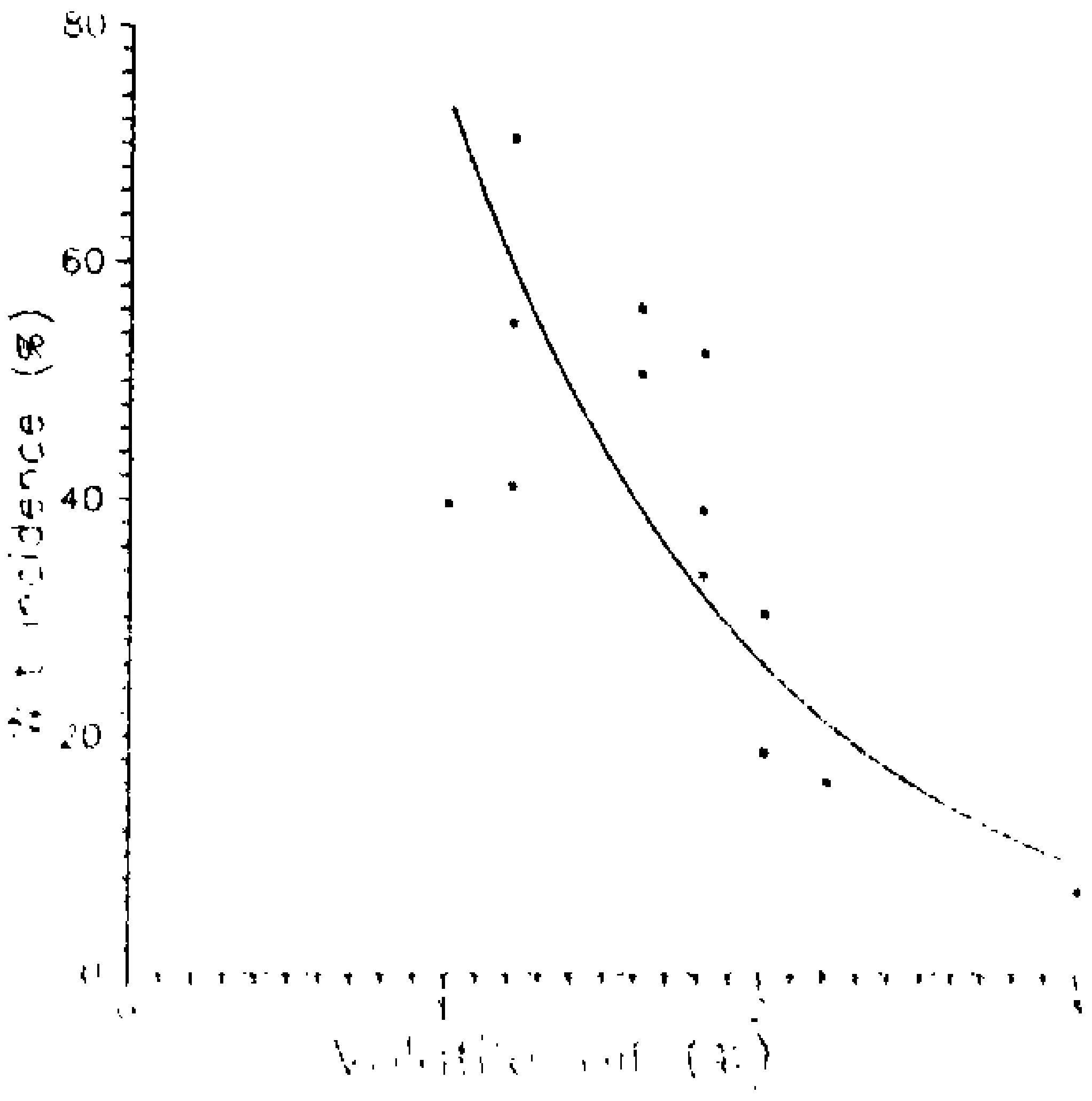

Figure 1. Relation between volatile oil and wilt incidence in cumin. The line represents the regression line ($Y = \exp(-1.03164x)$ 205.276).